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**Interactive Demand-
Shifting in the
Context of Domestic
Micro-Generation**

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ABSTRACT

The combination of ubiquitous computing and emerging energy technologies is radically changing the home energy landscape. Domestic micro-generation, dominated by solar photovoltaic, is increasing at a rapid pace. This represents an opportunity for creating and altering energy behaviours. However, these transformations generate new challenges that we call the domestic energy gap: domestic electricity consumption and micro-generation are out of sync. Micro-generation is mainly uncontrollable production relying on weather while domestic energy consumption tends to happen mostly during the evening. This thesis focuses on understanding and supporting new domestic practices in the context of domestic solar electricity generation, looking at ‘Demand-Shifting’. Specifically, we look at *how can digital tools leverage Demand-Shifting practices in the context of domestic micro-generation?* Relying on a mixed-method approach, we provide a qualitative and quantitative answer with the collaboration of 38 participating households in several field studies including two spanning more than eight months. Through a deep investigation of laundry and electric mobility routines in the context of domestic micro-generation, we emphasised a natural engagement into Demand-Shifting which appeared as a complex and time-consuming task for participants which was not visible when we analysed their quantitative data. We revealed this complexity through Participatory Data Analyses, a method we designed to analyse the data in collaboration with the participating householders. This provided us with a comprehensive view of the relationship between domestic micro-generation and daily routines. Finally, we highlight the need for timely and contextual support through the deployment of interventions in-the-wild. Building on discussions of our findings in perspective of the literature, we propose a conceptual framework to support domestic interactive Demand-Shifting.

RESUME EN FRANÇAIS

La combinaison de l'internet des objets et des nouvelles technologies liées à l'énergie transforme le paysage de l'énergie dans la maison. Les installations de micro générateurs, dominées par les panneaux solaires photovoltaïques, sont en constante progression. C'est une opportunité pour la création et l'altération des comportements énergétiques. Cependant, ces transformations créent également un nouveau défi que l'on appelle le « différentiel énergétique » à l'échelle de la maison : la consommation et la génération d'électricité des ménages sont désynchronisées. En effet, la génération locale est majoritairement incontrôlable et dépendante des conditions météorologiques alors que la consommation des ménages a tendance à se concentrer en soirée.

Cette thèse vise à comprendre et encourager les pratiques de déplacement des consommations émergentes dans les ménages équipés de panneaux solaires photovoltaïques. En particulier, nous observons « **Comment les outils numériques peuvent-ils tirer parti des pratiques de déplacement des consommations dans le contexte de micro génération domestique ?** ». Nous adressons cette problématique en trois étapes. Premièrement, il est nécessaire de construire une compréhension qualitative de l'impact potentiel. Quelles sont les pratiques, leurs conditions et leurs flexibilités ? Existe-t-il une cohérence de ces pratiques dans le temps, entre les ménages ou entre les appareils ménagers ? D'un point de vue quantitatif, quels sont les bénéfices potentiels de telles pratiques ?

RQ1. Comment les pratiques de déplacement de consommation prennent place dans le contexte de la génération domestique d'électricité de source solaire ?

Se focaliser sur la consommation d'électricité des ménages amène à porter une attention particulière à donner aux résidents, en particulier quand il s'agit de pics de consommation. Est-ce que les retours d'information traditionnels tels que « l'eco-feedback » permettent de supporter les nouvelles pratiques liées à l'énergie ? Dans le cas contraire, quels sont les limites des systèmes actuels et les nouvelles fonctionnalités requises ?

RQ2. Quel sont les éléments nécessaires pour l'interaction entre le système et les résidents quand l'objectif est de supporter les pratiques de déplacement des consommations ?

Se basant sur RQ1 et RQ2 :

RQ3. Comment peut-on concevoir un système numérique réaliste et interactif pour supporter le déplacement des consommations ?

Pour adresser ces questions de recherches nous avons combiné des approches empiriques et d'ingénierie, se renforçant et s'informant mutuellement les unes et les autres pour fournir une solution générale. Cela inclut la collection de données qualitatives et quantitatives, des analyses en collaboration avec les participants, des études longitudinales, des interviews, du co-design, des simulations et des tests en condition réelles. Tout au long de cette thèse, nous avons utilisé une méthodologie centrée sur l'utilisateur à chaque étape pour informer et valider la recherche.

Étude Utilisateur A : Comprendre la Relation entre Production et Consommation d'Électricité

À travers la première étude nous avons exploré la relation entre la production locale d'électricité de source solaire et la consommation des ménages. Nous avons utilisé une méthode appelée « Technology Probes » dont l'objectif vise à provoquer des idées et des commentaires de la part des participants. Nous avons développé sept concepts de visualisation que nous avons déployé dans six ménages pour une durée d'une à deux semaines. Affiché sur des tablettes électroniques, ces concepts représentaient par exemple un cadran à aiguille montrant la production locale instantanée ou une batterie représentant le niveau d'énergie « verte » disponible.

Nos résultats reflètent la littérature, montrant l'impact de la production d'électricité domestique sur les comportements et les pratiques, mais soulignent également le besoin de plus amples investigations pour les clarifier. Les participants ont parfois une compréhension erronée sur la quantité d'électricité qu'ils génèrent et quand. Nous soulignons également le besoin de plus ample recherche pour comprendre la relation entre génération et consommation.

Enfin, les participants ont particulièrement apprécié les fonctionnalités de prédiction telles que la prédiction de génération locale. Ils ont l'habitude de planifier les prochains jours en fonction des prévisions météorologiques et leur production d'électricité solaire a une place importante dans leurs routines quotidiennes. Regarder de l'avant semble une fonctionnalité importante dans le contexte de production locale.

Étude B : Analyser l'Activité « Faire la Lessive » dans les Ménages avec Panneaux Solaires

Pour comprendre plus en détails la relation entre la production locale et l'utilisation des appareils ménagers, nous avons concentré nos recherches sur l'utilisation de la machine à laver dans 18 ménages. Nous avons collecté les données d'électricité grâce à des compteurs et des prises intelligentes sur une période huit mois : l'électricité importée et exporté vers le réseau électrique, l'électricité produite par les panneaux solaires et la consommation électrique de la machine à laver.

Nous avons quantifié le potentiel de déplacement du temps d'utilisation de la machine à laver. Cela augmenterait de manière significative le pourcentage d'électricité provenant des panneaux solaires dans la consommation de la machine à laver, alors que le bénéfice financier à l'échelle de la maison serait négligeable. Ce résultat est directement lié à la faible consommation de la machine à laver. Nous avons également exploré la répartition de l'utilisation de la machine à laver au court de la journée et de la semaine en relation avec l'énergie solaire. Enfin, notre algorithme de « Meilleur Déplacement Vert » nous a permis d'évaluer le potentiel de déplacement des consommations de la machine à laver.

L'analyse exploratoire de ces données nous a permis de comprendre comment la génération locale d'électricité est consommée. Cependant, notre objectif visait à comprendre « pourquoi » elle était ainsi. Nous avons donc conçu et implémenté une analyse participative des données (PDA) pour compléter notre interprétation avec celle des participants. Cette analyse complète la collection et l'analyse des données avec trois étapes complémentaires : Premièrement, nous avons utilisé les données collectées, notre interprétation initiale et notre expertise pour concevoir des visualisations de haut niveau représentant l'activité 'faire la lessive' dans le contexte de production d'électricité de source solaire pour chacun de nos participants. Ensuite, nous avons conduit une interview avec chaque participant pour construire une conversation autour de ces visualisations (leur propres données). Enfin, combinant notre interprétation avec celle des participants, nous avons formulé une compréhension de cette routine ménagère.

Nous avons mis en évidence la complexité de l'environnement et le processus de décisions autour du déplacement des consommations et noté que la synchronisation et l'interaction entre les appareils ménagers sont des obstacles majeurs pour le déplacement interactif des consommations qui demandent de plus amples explorations. Alors que nous avons mis en évidence l'engagement et la volonté de s'engager dans le déplacement interactif des consommations, ce processus prend du temps et nécessite la considération de

multiples paramètres, de la prédiction de la production d'électricité et de la météo jusqu'à des informations contextuelles liées au ménage. Les utilisateurs ont accès à un nombre croissant mais toujours limité d'information et le déplacement des consommations se fait manuellement. Cela souligne le challenge de réduire les efforts en fournissant un support à ces pratiques sans réduire l'engagement qui émerge de ce contexte.

Étude C : Déployer des Interventions pour Supporter le Déplacement des Consommations

Reposant sur les conclusions de l'étude B, cette troisième étude visait à conduire des interventions en conditions réelles autour de la machine à laver pour le support du déplacement des consommations. Nous avons expérimenté différents niveaux d'information (données brutes, valeurs calculées, suggestions avancées), temps d'interactions (passé, temps réel, future) et moyens de communication (courriels, SMS, affichages dédiés). Utiliser la technologie comme un support est une solution viable et efficace. Nous avons souligné que l'engagement et l'utilité de nos interventions étaient croissantes de l'information décontextualisée vers le contrôle contextuel embarqué (du courriel vers la tablette électronique contrôlant la machine à laver). Le support à l'énergie devrait évoluer de la boucle d'information rétroactive vers la suggestion proactive. Dans ce contexte, les décisions à propos du temps d'exécution de la machine à laver sont *négociées* avec l'utilisateur.

Notre analyse avec les participants a révélé la complexité de la dynamique entre les habitants, les appareils ménagers et les objectifs. Étudier les activités autour de la machine à laver nous a conduit à une *conversation* avec les habitants qui ne se préoccupent pas spécifiquement de l'énergie dans le ménage, et donc vers un élargissement de l'audience. Mis à part les défis techniques, les appareils offrant des opportunités potentielles pour le déplacement des consommations varient d'un ménage à l'autre et au cours du temps. Enfin, maximiser l'utilisation de l'électricité produite localement est un objectif parmi d'autres, incluant le coût financier et le confort de l'utilisateur. Notre déploiement d'interactions utilisateurs a mis en évidence que les prédictions et les temps d'interventions sont des éléments essentiels pour le support du déplacement des consommations. Les interactions basées sur des prédictions, du planning et des suggestions sont plus appropriées que l'information fournie habituellement qui se concentre sur les événements passés. L'utilisation du retour d'information est limitée car il n'y a pas grand-chose à apprendre du passé dans ce contexte. Les supports utilisateurs devraient être proactifs et le plus contextuel possible. De plus, un équilibre doit être trouvé entre action manuelle et automatique pour réduire l'effort de l'utilisateur sans réduire son engagement.

À travers ces interventions nous avons atteint les limites d'une étude se concentrant sur un seul appareil ménager. Bien qu'elles nous aient fourni les éléments clés pour comprendre la routine 'faire la lessive', nos interventions ont révélé d'importantes corrélations entre les appareils rendant difficile les interventions sur un seul d'entre eux.

Étude D : Étendre le Contexte de Recherche à un Appareils Ménager Émergeant : la Voiture Électrique

Notre objective avec cette dernière étude de terrain visait à étendre la vision construite au cours des études précédentes qui se concentraient sur la machine à laver : un appareil ménager conventionnel dont la consommation d'électricité est modérée. Nous avons exploré les routines autour de la mobilité électrique, d'abord au sens large puis spécifiquement dans la maison, soulignant une absence dans la littérature : la voiture électrique comme appareil ménagé et sa connexion avec la production d'électricité domestique. Nous avons fourni une analyse quantitative et qualitative de ce contexte.

À travers notre exploration nous avons identifié une opportunité : la plupart des participants ont confiance en leur voiture électrique et son rechargement à la maison. Cela contraste avec la littérature se concentrant jusqu'à présent sur l'anxiété liée à l'autonomie limitée de ces véhicules et aux stations de rechargement publiques souvent défectueuses ou occupées. De plus nous avons souligné que le lien entre la voiture électrique et la production d'électricité domestique repose sur le désir d'être auto suffisant. Cet objectif répond aux mêmes conditions que minimiser l'impact sur l'environnement. Notre analyse quantitative a donné un aperçu des opportunités d'autosuffisance, montrant des proportions équivalentes entre la génération provenant des panneaux solaires et la consommation des véhicules électriques. Cependant, à travers une analyse plus précise nous avons mis en évidence qu'une partie seulement très limitée de l'énergie solaire est utilisée pour charger le véhicule électrique.

Nous avons fait écho à nos résultats précédents. Viser les routines de mobilité élargi l'audience autour de l'énergie. Alors qu'il y a techniquement un potentiel important d'optimisation en déplaçant le temps de charge des voitures électriques, nous avons tout de même mis en évidence quelques opportunités de flexibilité dans le temps. Nous avons confirmé l'image déjà complexe et dynamique des routines domestiques commencé avec le cas de la machine à laver. Alors que la machine à laver était un appareil bien connu qui ne nécessite pas de support particulier, nous avons souligné le besoin d'un support pour la voiture électrique dans la maison.

Cela représente une opportunité pour combiner le support au déplacement des consommations directement avec un support général à la mobilité électrique.

Modèle pour le Déplacement Interactif des Consommations

Dans la dernière étape de ce projet de recherche nous avons organisé les résultats de nos études utilisateurs A, B, C et D en perspective de la littérature pour formaliser un modèle conceptuel pour le déplacement interactif des consommations (iDS pour interactive Demand-Shifting). Ce modèle repose sur l'interaction entre quatre éléments clés : les temps d'interaction, la participation des résidents, les objectifs et les appareils ménagers.

Nous proposons une « conversation numérique » pour supporter une interaction consistante de haut niveau entre les utilisateurs et le système. Enfin, nous mettons en pratique le modèle iDS à travers la conception d'un potentiel système interactif de déplacement des consommations.

Contributions

Nous fournissons une compréhension détaillée du « différentiel énergétique » et de la complexité de l'infrastructure du réseau électrique tant à l'échelle nationale qu'à l'échelle de la maison. Cette thèse a mis en évidence des bénéfices financiers limités pour un ménage. Cependant, en s'adaptant facilement à tous les ménages, cela représente un impact significatif sur le réseau électrique pour un investissement limité. L'objectif principal de cette thèse est de soutenir la consommation d'énergie durable. Les pratiques sont susceptibles d'être plus durable au fil du temps si elles sont d'abord naturellement mises en œuvre par les ménages eux-mêmes au lieu d'être poussé vers eux dans le but de changer leur comportement.

Déjà souligné dans la littérature, la gestion de l'énergie domestique doit se faire au niveau des activités et des routines et non pas sur l'analyse hors contexte des profils consommations. Sur cette base, nous proposons une « conversation numérique », permettant des interactions de haut niveau entre les ménages et le système, posant les fondations d'une *négociation* vers une gestion durable de l'énergie. Avec une dimension utilisateur approfondie, nous avons formulé une taxonomie des appareils ménagers. Cette taxonomie considère les perspectives du monde réel recueillies tout au long de cette thèse, considérant la diversité et la flexibilité nécessaire à la gestion de l'énergie dans la maison. En combinaison avec la conversation numérique, ils fournissent la base d'un système de gestion de l'énergie domestique plus durable pour l'ensemble du ménage.

Nous avons souligné l'importance du temps des interventions. Déplacer les consommations, c'est non seulement trouver le bon moment pour consommer de l'électricité mais aussi le bon moment pour interagir

avec les résidents. En particulier, les suggestions proactives et les interventions contextuelles offre aux ménages la possibilité d'intervenir à temps avec les informations et le soutien nécessaires.

Pour construire une compréhension précise des routines internes, nous avons combiné plusieurs méthodes. Nous avons conçu et mis en œuvre une analyse de données participative (PDA) qui combine des données quantitatives et des données qualitatives pour analyser le contexte de la maison en collaboration avec les résidents. Cette méthode a été un moyen efficace pour confirmer nos premières interprétations, mais aussi pour enrichir à la fois notre analyse quantitative et qualitative avec des éléments précis du contexte.

DECLARATION

While I led and performed all the steps of the research presented in this dissertation, I performed parts of this work in collaboration. First, my supervisors assisted in the Technology Probes study (Chapter 4 p.65) at the early stages of this project. I provided the implementations of the probes and attended the interviews. I published and discussed my reflection on this methodology at a CHI'13 workshop. Second, I collaborated with E.ON throughout the project to access the infrastructure of the participating households. E.ON provided valuable technical support in the deployment of the Demand-Shifting interventions (Chapter 6 p.107). Finally, I led the EV study in collaboration with Stefan Foell who conducted half of the exploratory interviews (Chapter 7 p.126).

Some ideas and figures have appeared previously in the following publications:

Blaine Price, Janet van der Linden, Jacky Bourgeois, and Gerd Kortuem. When looking out of the window is not enough: informing the design of in-home technologies for domestic energy microgeneration. In First International Conference on Information and Communication Technologies for Sustainability, February 2013.

URL <http://oro.open.ac.uk/35460>.

Jacky Bourgeois, Janet van der Linden, Blaine Price, and Gerd Kortuem. Technology probes: experiences with home energy feedback. In Methods for Studying Technology in the Home, April/Spring 2013. URL <http://oro.open.ac.uk/36791>. Methods for Studying Technology in the Home was a workshop hold as part of the ACM SIGCHI Conference on Human Factors in Computing Systems (CHI) in Paris, France from 27th April - 2nd May 2013. ISBN: 978-1-4503-1952-2.

Jacky Bourgeois, Janet van der Linden, Gerd Kortuem, Blaine A. Price, and Christopher Rimmer. Conversations with my washing machine: An in-the-wild study of demand shifting with self-generated energy. In Proceedings of the 2014 ACM International Joint Conference on Pervasive and Ubiquitous Computing, UbiComp '14, pages 459–470, New York, NY, USA, 2014a. ACM. ISBN 978-1-4503-2968-2. doi: 10.1145/2632048.2632106. URL <http://oro.open.ac.uk/40465>.

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2nd International Conference on ICT for Sustainability (ICT4S 2014), August 2014b. URL <http://oro.open.ac.uk/40466>.

Bourgeois, Jacky; Foell, Stefan; Kortuem, Gerd; Price, Blaine; van der Linden, Janet; Elbanhawy, Eiman and Rimmer, Christopher (2015). Harvesting green miles from my roof: an investigation into self-sufficient mobility with electric vehicles. In: 2015 ACM International Joint Conference on Pervasive and Ubiquitous Computing (UbiComp 2015), 7-11 September 2015, Osaka. URL <http://oro.open.ac.uk/43874>.

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Figure 2-9c p.30: The local energy indicator (Pierce & Paulos, 2012). ACM Copyright Clearance

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Figure 2-9e p.30: The carbon intensity – Approval from the author by email.

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ENVIRONMENTAL IMPACT

The overarching objective of this research project is more sustainable energy use. From that perspective, it is important to highlight the impact of this research on the environment over the last 3 years.

Table 1-1 details the transport directly related to the work for this thesis. We can observe that my travels to conferences generated 4.6 tonnes of CO₂ while my daily commutes over 3 years avoided the emission of 614kg of CO₂.

Table 1-1 Impact carbon of the transport during this thesis.

Trip	Transport Mode	Purpose	Quantity	Distance (Miles)	kgCO ₂
Milton Keynes ⇌ Paris	Train	CHI	x1	700	+3.5 ²
Milton Keynes ⇌ Zurich	Plane	UbiComp	x1	1023	+160 ¹
Lyon ⇌ Stockholm	Plane	ICT4s	x1	2402	+530 ¹
Lyon ⇌ Oxford	Plane	Behave	x1	964	+270 ¹
Lyon → Seattle → Milton Keynes	Plane	UbiComp	x1	5730 + 5223	+810 + 730 ¹
Rennes ⇌ Madrid	Train/Plane	SustainIT	x1	460 + 1445	+2.4 ² + 230 ¹
Rennes ⇌ Osaka	Train/Plane	UbiComp	x1	460 + 13162	+2.4 ² + 1850 ¹
Milton Keynes ⇌ Rennes	Train	Co-tutelle	x5	5593	+28.8 ²
Milton Keynes	Bicycle	Commute	X600	1800	+0
Milton Keynes	Bicycle	Interviews	x1	60	+0
Rennes	Bicycle	Commute	x300	1200	+0
Total				40222	4617.1

The raw estimation of paper consumption over three years is about seven reams (18kg, 6% of a tree per ream³). This value can be put in perspective of advertisements received in mailbox. In France, a household without the ‘Stop Pub’ sticker on its mailbox, receives 2.7kg of paper per month in 2014⁴. This research project represents about 6.5 months of domestic advertising.

¹ Flight carbon footprint calculated on <http://www.carbonneutralcalculator.com/flightcalculator.aspx>

² TGV, 5.14gCO₂/miles/passenger (SNCF)

³ <http://conservatree.org/learn/EnviroIssues/TreeStats.shtml>

⁴ UFC Que Choisir – Service des études « Publicité dans les boîtes aux lettres : La grande distribution en fait plus que jamais des tonnes », 2014

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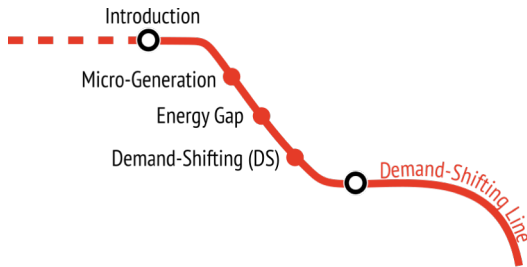


Figure 1-1 Head of the Demand-Shifting line, red thread of this dissertation.

Following the analogy of underground maps, we build the network of this dissertation throughout the document (Full map p. 182).

1

Introduction

Supporting the Future Energy Strategy

‘Fire made us human, fossil fuels made us modern, but now we need a new fire that makes us safe, secure, healthy and durable.’

AMORY LOVINS, *REINVENTING FIRE*, 2012

Amory Lovins stresses the need for a new ‘fire’, a radical change towards sustainability. We believe that this ‘fire’ will come through the harmonisation of our planet’s resources with people’s aspiration. This thesis makes a modest step towards this objective, looking at **How can digital tools leverage Demand-Shifting practices in the context of domestic micro-generation?**

1.1 DOMESTIC MICRO-GENERATION

Distributed electricity generation is considered an important piece in the puzzle of our future energy strategy (Lovins, Amory B. and Rocky Mountain Institute, 2011). Germany, a leader in renewable energy (21% of the global installed solar PV capacity), derives about 7%⁵ (2014) of its electricity from solar energy. It shows concrete evidence of an energy transition taking place through alternative electricity generation such as **micro-generation** – any generation of heat or electricity up to 50kW or 45kW thermal⁶. In the UK, like in many countries, a national rollout requires energy suppliers to install smart meters along with an In-Home Display (IHD) in every household and small business by the end of 2020⁷. These devices provide real-time energy feedback and opportunities for energy control in each individual household. In combination with micro-generation, they are the core ingredients of the ‘smart grid’, an emerging electricity network consisting of small prosumer households that is more cost effective and more energy efficient.

⁵ Fraunhofer Institute for Solar Energy Systems (ISE), Photovoltaic report, March 2016

⁶ Including biomass, biofuels, fuel cells, water, wind, photovoltaics, solar power, geothermal sources, CHP (Energy Act, Chapter 20, 2004, p. 65)

⁷ DECC – Smart Metering Implementation Programme

Meanwhile, domestic micro-generation is increasing at a high pace, dominated by solar photovoltaic (PV). Today, we can buy solar PV installation kits in popular stores like IKEA. Even if the adoption of this technology remains slow, it means that potentially ordinary households can become ‘energy farmers’. Domestic heating and transport are also shifting to electricity based technologies. Typical examples are heat pumps and electric vehicles (EV). This new electric home electricity consumption will increase domestic energy consumption, representing already 27%⁸ of energy consumption in the UK (in 2014, including 25% of electricity⁹). While investments into insulation improvement and efficient appliances can reduce electricity consumption, householder’s behaviours impact this consumption too. This impact has been highlighted by showing variations between similar houses that cannot be explained by technical difference alone (Sonderegger, 1978; Hiller, 2012). Most citizens are unaware of what they can do to reduce consumption. Energy consumption feedback is a first step towards raising energy awareness and a few projects have already shown a significant impact on reducing overall consumption (Fischer, 2008; Darby, 2006). Yet, existing energy feedback are not sufficient for three reasons:

- First; this information is often in the form of incomprehensible values and graphs.
- Second; the concepts related to energy are hard to understand because of the invisible and intangible nature of energy and electricity.
- Finally, despite previous energy crises, electricity is commonly seen as an unlimited resource with few, if any, environmental drawbacks.

We can observe a contrast between the simplicity of using electricity and the difficulty for typical users to understand the various concepts associated with electricity. The emerging development of micro-generation and new electric appliances such as EVs adds another layer of complexity on top of this complex home electricity system. The overarching objective of the research about energy consumption feedback focuses on rising energy awareness and driving behaviour change towards energy consumption reduction. However, research on emerging practices in the context of micro-generation as well as their role in the design of future domestic energy management systems remains underexplored.

⁸ DECC – Energy Consumption in the UK (2015), Chapter 1: Overall energy consumption in the UK since 1970 (p.10)

⁹ DECC – Energy Consumption in the UK (2015), Chapter 3: Domestic energy consumption in the UK between 1970 and 2014 (p.6)

1.2 MICRO-GENERATION AND TRANSITION

Domestic micro-generation will play a major role to drive energy behaviour change (Devine-Wright, 2007). It does not only produce renewable energy, but brings the process of electricity production closer to where the electricity is consumed and makes energy more tangible (Dobbyn & Thomas, 2005).

Through the ‘grid lens’, domestic micro-generation is part of a global transition:

- from distant, centralised, on-demand, hidden, virtually unlimited and undifferentiated sources of electricity
- to much smaller scale, distributed, uncontrolled, local, personal, visible, limited, ‘green or dirty’, ‘free, cheap or expensive’ sources of electricity.

Through the ‘domestic lens’, households investigating technologies such as solar PV or EV make the implicit choice of building new or altering their daily routines. While households with solar PV are not forced to do so, most of them change their daily routines. In a study comparing households with and without micro-generation (Dobbyn & Thomas, 2005), Dobbyn and Thomas report that most of the households with micro-generation they interviewed developed a strong awareness about their energy use and the link between usage and generation. These households exhibit evidence of energy efficiency behaviour change but people were also reporting that they were feeling ‘good’ and ‘proud’ about their technology. Most householders tended to reduce their consumption and had shifted their consumption towards times when solar electricity generation was available.

Building on this work, Bergman and Eyre discuss the central role that micro-generation can play in the domestic energy transition (Bergman & Eyre, 2011). However, they highlight that ‘*maximising uptake of micro-generation is insufficient to maximise savings*’. This is because householders who invest in alternative energies are already engaged in a process of energy awareness, and are doing so out of both ‘green’ and financial interests. The renewables energy industry promises both green consumption and reduced energy bills. However, when households invest in domestic generation they are often left alone without the support or tools to help them understand how to optimise the use of these new energy sources. This research project aims to capitalise on these opportunities of transition and micro-generation, looking in depth at energy practices emerging from this context and designing digital tools to support householders through their implementation and deployment.

1.3 THE ENERGY GAP

Above, we have highlighted the increasing technical complexity of the home energy system. On top of that, these technologies are out of sync, producing and consuming electricity at different times, creating what we refer to as a domestic *energy gap*.

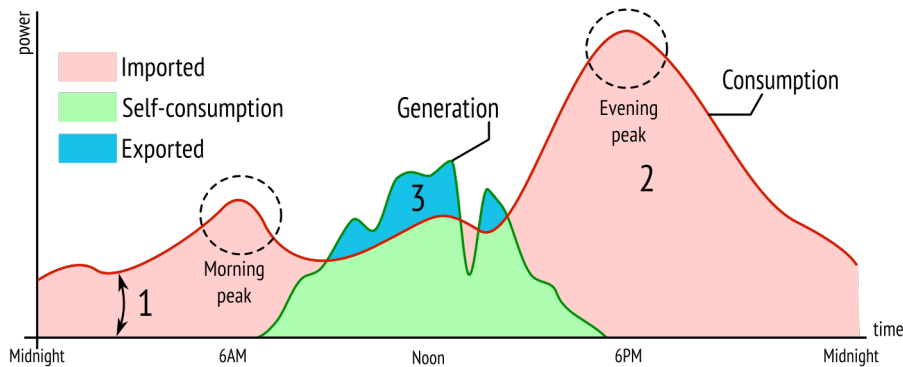


Figure 1-2 The energy gap in the residential context. 1: high consumption throughout the day, 2: peak time consumption, 3: peak time generation. Notes: This chart represents fictitious data to provide an overall yet simpler view (see Chapter 5 for actual chart)

We define the energy gap as this difference between the overall electricity consumption and the renewable electricity generation. In the context of domestic solar generation, the energy gap is a set of three issues (see

Figure 1-2):

1. It is generally acknowledged that overall, households consume too much electricity and should aim to reduce their consumption.
2. The domestic consumption pattern is not evenly distributed throughout the day. Instead it shows sharp peaks during the morning and the evening.
3. On the other hand, the peak of solar generation is at a different time, i.e. around noon. Since solar electricity generation and electricity consumption are out of sync renewable energy is not consumed locally.

Apart from reducing electricity consumption, **Demand-Shifting** is a method to reduce the energy gap. Demand-Shifting is a particular form of behaviour change where energy consumption is shifted towards *better* times, e.g. when the electricity cost is at its cheapest, the local generation is at its highest, etc. The literature also refers to ‘load shifting’ as a mechanism that aims to move the electricity load from the consumption peak hours (**Figure 1-2 2**) to off-peak hours during the day. In this thesis we refer to the term ‘Demand-Shifting’ as shifting an activity considering the interplay between householders, devices and the environment at a given time.

1.4 SUPPORTING DEMAND-SHIFTING TO REDUCE THE ENERGY GAP

In the previous section we emphasised the challenges and the opportunities of domestic electricity context. Electricity in the home is increasingly complex while there is some evidence that households with solar PV would like to optimise the use of their local generation. In this thesis we explore these issues in more depth to get a better understanding of what it is householders themselves are actually doing to exploit the potential of their locally generated electricity. In contrast with previous research focusing on driving behaviour change towards consumption reduction, this research will take a different approach and investigates how best to support behaviour changes to reduce the energy gap. More precisely, we focus on Demand-Shifting through the following research question for the thesis as a whole:

How can digital tools leverage Demand-Shifting practices in the context of domestic micro-generation?

We addressed this research question in three steps to explore, understand and support Demand-Shifting. We mixed engineering and empirical approaches, mutually strengthening and informing one another to provide an overall solution. This includes qualitative and quantitative research approaches through the collection of data from smart meters and other sensors, participatory data analysis, longitudinal studies, interviews, co-design, simulation and real world testing. Throughout this research project we used a user-centric methodology at each stage to inform and validate the research.

First, we developed a qualitative and quantitative understanding of Demand-Shifting practices and their potential impact. Who manages energy and demand-shifting in the household? What are the conditions, requirements and difficulties of this practice? From a quantitative perspective, what are the potential savings of Demand-Shifting? We frame this exploration through the following question:

RQ1. How do Demand-Shifting practices take place in the context of domestic solar generation?

In collaboration with E.ON, an International energy provider, we conducted four user studies focusing on laundry and electric mobility routines in the context of domestic solar electricity generation. We extracted a deep understanding of Demand-Shifting practices in the context of domestic solar electricity generation. In particular, we highlight how and why manual Demand-Shifting takes place. We emphasise the willingness of

most householders to manually implement Demand-Shifting behaviours but also the constraints and difficulties they encounter as part of normal day-to-day life. We provide a quantitative and qualitative evaluation of the potential of Demand-Shifting. To build this understanding of Demand-Shifting practices, we developed an in-the-wild methodology we call ‘Participatory Data Analysis’ (PDA). Combining quantitative and qualitative data into individual and personalised visualisations, this methodology allows us to collaborate with participating households to extract necessary details of their daily routines in order to prototype supportive digital tools. We used this methodology in both studies with other methods.

Second, we look at the interaction between the householder and the system. How do we best support householders in their attempt to manage their consumption and generation? Is typical energy feedback a suitable way to provide this Demand-Shifting support? What are the constraints and the new requirements for this interaction?

RQ2. What are the requirements for the interaction between system and householders when the aim is to support Demand-Shifting practices?

We explore the context of domestic micro-generation, conducting longitudinal energy data collections and multiple interviews with 38 participating households. Relying on a combination of quantitative and qualitative analysis, we provide design and user evaluations of user interactions to support Demand-Shifting. Through these designs we highlight major differences between *driving behaviour change* and *supporting emerging energy practices*. While information such as energy feedback increases energy awareness, we highlight that supporting Demand-Shifting requires a more *predictive, contextualised* and *digested* form of interaction.

Finally, we use the adaptation and support requirements (RQ1) with the user interaction (RQ2) and the perspective of the literature to design a system supporting domestic Demand-Shifting.

RQ3. How can we design a realistic and interactive digital system to support domestic Demand-Shifting?

Through the design of a conceptual framework for interactive Demand-Shifting (iDS), we present a realistic view of the Demand-Shifting potential. We show the feasibility of the proposed solution and the remaining challenges.

1.5 DEMAND-SHIFTING LINE

This thesis is a journey towards an interactive Demand-Shifting system. **Figure 1-3** illustrates the main stations along the way, through exploration, understanding and intervention.

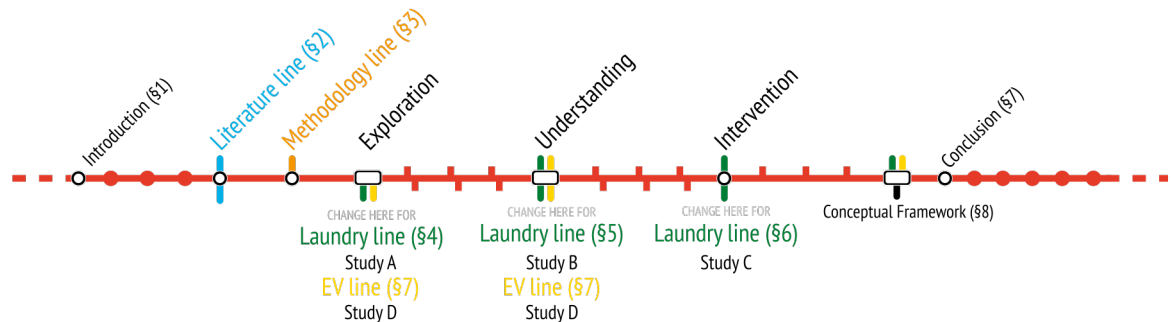


Figure 1-3 Demand-Shifting line.

In **Chapter 2** we take on board the background and existing literature of this research. First, we look at the context with different lenses from the electricity grid to the home electricity system. Then, we provide the motivations and a definition of the Demand-Shifting mechanism. We review the three existing approaches to this mechanism – Demand-Side Management (DSM), eco-feedback and supportive tools. Finally, we detail the main ingredients for the Demand-Shifting mechanism.

Diving into the research methodology, **Chapter 3** aims to motivate the user-centric approach of this project. We present the epistemology of the research along the evaluation and investigation methods we selected to conduct this project, as well as our collaboration with E.ON.

In **Chapter 4** we present our study A, a first investigation into the domestic solar generation context focusing on the connection between the domestic solar generation and daily routines. Then, study B led us towards a better understanding of the Demand-Shifting practices with a focus on the washing machine and the laundry routines (**Chapter 5**): How does self-generated electricity alter a longstanding household routine? In **Chapter 6** we present the study C in which we deployed concrete in-home interventions to support Demand-Shifting practices around the washing machine. Finally, we complement this view with the study D (**Chapter 7**) through an exploration of Electric Vehicles (EV) and emerging electric mobility behaviours. How do EV routines modify the home routines? How does it connect to the local generation?

Chapter 8 provides a discussion of the user studies A, B, C and D and organise the key findings into a conceptual framework for interactive Demand-Shifting (iDS). We bridge the gap between engineering and user-centric research through the design of an iDS system.

Summarising the research project, the **Chapter 9** concludes this dissertation addressing the research questions and highlighting the contributions and the limitations.

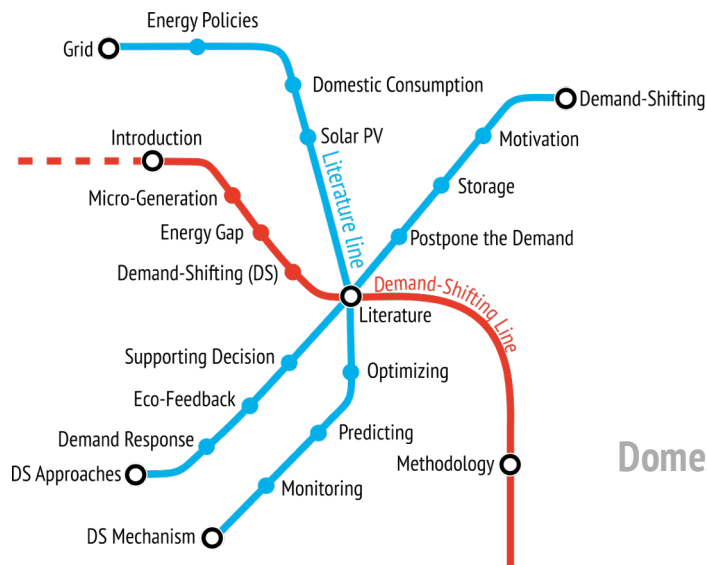


Figure 2-1 The literature line. We review the existing literature from the background to the definition of Demand-Shifting (DS); then beyond, looking at DS approaches and DS mechanism.

Literature Review

Domestic Electricity Demand-Shifting

'I have not failed. I've just found 10,000 ways that won't work.'

THOMAS A. EDISON

In this thesis, we look at opportunities to support householders through digital tools in the context of domestic micro-generation. This topic is spanning across the domains of energy, human-computer interaction and software engineering. Hence, this chapter brings the necessary knowledge of these domains while building the connections between them. First, we discuss the energy terminology and key issues that motivate this work. We draw the path from the grid towards domestic electricity and micro-generation. Second, we use this knowledge to properly define and motivate the Demand-Shifting mechanism. We strengthen these motivations with early evidence from the literature. Third, we look across domains at existing approaches for domestic electricity Demand-Shifting from Demand Side Management to eco-feedback and supportive systems. For each of these approaches we look specifically at three perspectives: the objectives, the algorithms and the implementations. Finally, we use these perspectives to funnel our path through software engineering and detail the key challenges and requirements for the Demand-Shifting mechanism.

2.1 TOWARDS DOMESTIC ELECTRICITY DEMAND-SHIFTING

To understand the challenges behind electricity coming on-demand out of any power outlet, it is necessary to gain an overall perspective, looking at the wider environment of electricity. What are the fundamental dimensions and principles of electricity? How do we produce electricity? And how do we route it towards the power outlet? Through this section we draw the path towards domestic electricity Demand-Shifting from the

electricity grid to the individual house and micro-generation while providing the necessary terminology. This section focuses on three dimensions of the grid that motivate and drive this research:

- First, we introduce the carbon intensity of the grid, what it represents and why we use it as a relevant measure of environmental impact in this project;
- Second, we highlight the critical requirement of balancing electricity generation and consumption, shedding light on its impacts and challenges. This is the main argument for a better energy management;
- Finally, we focus on energy losses, highlighting the significant amount of electricity lost during the transport from suppliers to consumers. This is another motivation for consuming electricity generated locally.

2.1.1 GENERATION AND NATIONAL ENERGY POLICIES

In most developed countries, the history of electricity drove the current layout of the grid: a centralised electricity network dominated by a few large generators. These power plants produce electricity from various raw materials such as gas, oil, coal, uranium and water. For about a decade, the use of wind and solar energy have begun to be viable technologies in the landscape of electricity generation. Each of these fuels, from the conventional coal power plant to the latest wind turbine or solar photovoltaic technology, impacts the *carbon intensity* of the electricity consumed by the end-user. The carbon intensity – in grams of carbon dioxide per kilowatt-hour (gCO₂/kWh) – represents the amount of CO₂ emitted to produce electricity¹⁰. It only considers the carbon dioxide emitted as the consequence of electricity generation. In contrast, the *carbon footprint* (gCO₂eq/kWh – ‘eq’ standing for *equivalent*) includes the entire life cycle of the power plant. For example, solar photovoltaics require currently a significant amount of energy to be produced and recycle. This increases their *carbon footprint*. However, the production of electricity coming out of solar photovoltaics does not emit CO₂, keeping their *carbon intensity* to zero. Thus, domestic electricity consumption plays a role on the *carbon intensity* by controlling how and when the electricity is consumed.

The Example of UK’s National Grid

Balancing supply and demand is the prerequisite for a stable electricity grid and guarantees a secure supply. By nature, an electricity network fails when the difference between supply and demand is too high. This can cause power failure, dropping electricity for an entire region. Over the last decades, electricity providers learned to predict the electricity demand for the following hours and days in order to anticipate the required electricity production. This allows, for example, warming up a coal or gas power plant and thus being ready for a peak

¹⁰ IEA’s definition of the carbon intensity: <http://www.iea.org/etp/tracking/esci/>

demand. This relies on finely tuning the production of controllable power generation. This challenge of meeting the demand is harder with the development of electricity production based on renewable energy such as solar and wind. In that case, electricity providers need to anticipate both the demand and the renewable electricity generation in order to compensate with controllable generation to ensure the balance of the grid. For example, a solar eclipse and hot summer days have provoked both a drop in supply and over-production in Germany in recent years¹¹.

To describe the challenges of the multiple types of fuel supplying electricity towards the grid, we look at a concrete example of the grid mix on May 27th 2015 in the UK. The generation of the UK's main power plants are reported every 30 minutes on the BM website¹² (solid lines in **Figure 2-2c**). Such data does not exist for micro-generation yet. In fact, there is no grid scale monitoring of micro-generation in the UK at the moment. However, the National Grid website¹³ provide a fine-grain prediction of solar and wind micro-generation (dashed lines in **Figure 2-2c**). These estimations take into account the installed capacity and the weather.

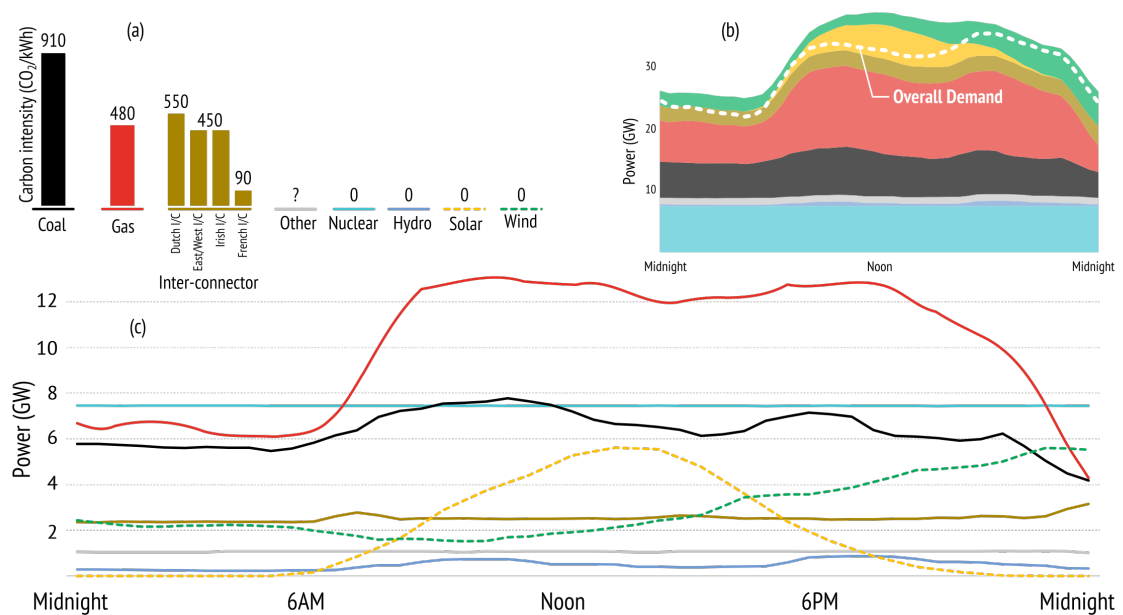


Figure 2-2 UK's electricity generation by type of fuel in GW on May 27th, 2015. a: carbon intensity per fuel in CO₂/kWh (www.gridcarbon.uk); b: stacked generation by type of fuel with overall demand; c: Generation by type of fuel. Notes: Solid lines are monitored data while dashed lines (solar and wind) are estimations based on installed capacity and weather. Inter-Connectors are grid connections with other countries.

Based on this combination of data, **Figure 2-2c** presents a view of the UK's electricity generation on May 27th, when conventional fuels were dominating as usual. The straight light blue line under 8GW represents the

¹¹ Eclipse in Germany: <http://www.greentechmedia.com/articles/read/German-and-European-Power-Grids-Civilization-Intact-Following-Solar-Eclips>

¹² BM reports: <http://bmreports.com>

¹³ Estimation from NationalGrid: <http://www2.nationalgrid.com/UK/Industry-information/Electricity-transmission-operational-data/Data-Explorer/>

nuclear production, a technology with low carbon intensity that cannot be adjusted quickly in time. In contrast, the coal (black) and gas (red) productions are the most reactive type of power plant to the demand. However, they have the highest carbon intensity. We can observe this level in **Figure 2-2a**, ranking the carbon intensity of the main fuels used in the UK.

Technologies based on renewable energy such as wind turbines (green), solar PV (yellow) and hydroelectric dams (in blue) productions appear at the bottom of the chart. While hydro energy can be controlled and used at specific time such as in the morning and evening peaks, the production based on the wind depends on the weather variation. On the presented day, there was a fair bit of wind blowing in the evening which reduced the grid's carbon intensity. It has no impact on other sources in the evening, because all sources are needed to compensate the evening peak demand. We can also notice the impact of solar PV generation in the middle of the day, leading to a slight reduction of the production from coal and gas. Although, most of this valley in the middle of the day relates the decreasing consumption (white dashed line in **Figure 2-2b**). While these renewable energies provide zero-carbon emission electricity during production, it is important to highlight their impact on the grid. Whether we are in the middle of a hot summer day or in a cold winter evening without wind, the electricity generation has to match electricity demand. By nature, the electricity grid has to keep this equilibrium to remain stable. This constraint forces energy providers to keep conventional coal and gas power plant ready to ramp up in case of over or under production. It implies financial cost and additional carbon emission.

The inter-connectors (I/C) highlight the global context of electricity (orange). Even though the UK is an island, its electricity network is connected to the French, the Irish, the Dutch and the Eastern European electricity grids. A storm blowing in Ireland or a very hot summer day in Germany has an impact on the whole network.

While we notice variations of the grid mix over time, there are also significant differences between each country's grid. For instance, the French national energy policy led to a network dominated by nuclear generation. This makes the introduction of solar PV and wind turbines challenging because there is not enough reactive production to balance a drop in renewable production. In contrast, the German national energy policy recently pushed for the development of renewables in a plan to remove nuclear generation by 2022. The country beats its own records of solar PV generation every summer, threatening the grid stability. In fact, such

a large penetration of uncontrollable power generation risks to overload the grid, leading to similar issues as an over consumption in winter. To maintain the stability, generation and consumption must remain balanced.

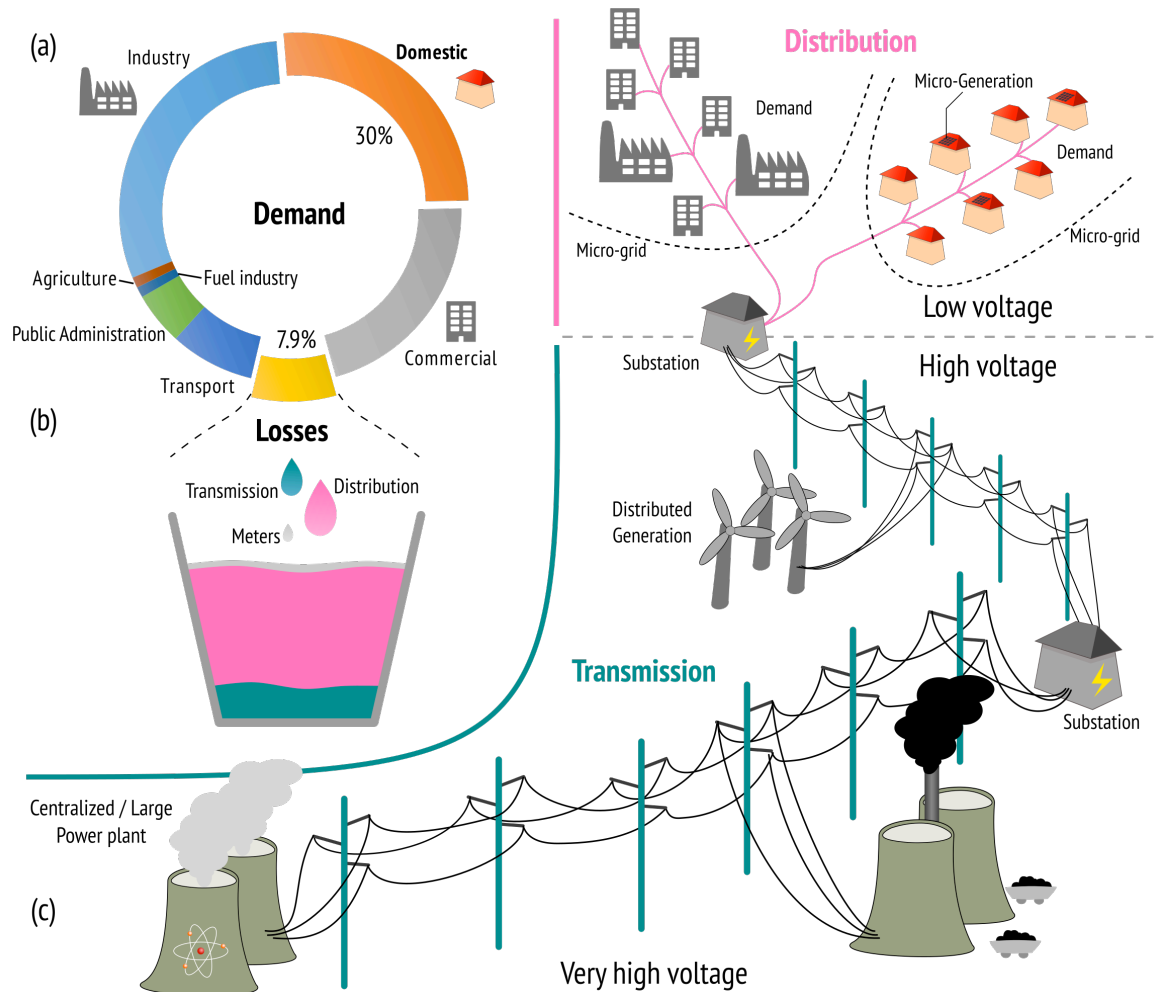


Figure 2-3 From supply to demand. a: the electricity demand per sectors; b: energy losses from generation to consumption through transport and transformations; c: electricity journey from generation to consumption.

From Supply to Demand

Generation is only a part of the electricity grid. The path from the power plants to the consumer includes three important steps (**Figure 2-3**). Because most of the electricity is produced by a few large power plants, it requires high-voltage *transmission* over long distance. As a next step, substations *transform* electricity into low voltage to be consumed by end-user consumers including households. Finally, a *distribution* network connects each consumer to the grid (**Figure 2-3c**). These various steps and the transportation of electricity over long distances involve electricity getting lost. In the UK, energy losses accounted for 28.5 TWh, representing 7.9 per cent of electricity demand in 2014¹⁴. In contrast, the entire domestic electricity consumption represents approximately 30 per cent (**Figure 2-3a**). This makes solar PV and wind turbines the most relevant

¹⁴ DUKES 2015, Chapter 5: Electricity (p.116)

renewable technologies, as they produce electricity near the consumer. However, this local production has to match the domestic consumption to avoid the losses implied by the distribution.

In the previous section we presented real-time data of the UK's major power plants, mentioning only an estimation of solar and wind micro-generation. Small generators and most consumers do not currently share any real-time information about what they produce or consume. Thus, most of the grid balance is achieved as in previous decades relying on the prediction of the consumption and more recently the prediction of the generation. Smart grids are networks that monitor and manage the transport of electricity from all generation sources to meet the varying electricity demands of end-users¹⁵. For instance, in the UK, like in many countries, a national rollout requires energy suppliers to install smart meters along with an In-Home Display (IHD) in every household and small businesses by the end of 2020¹⁶. These devices represent the core of the smart grid, providing real-time energy feedback and opportunities for fine-grain production and generation monitoring. Real-time information and communication across the grid promises more dynamic and efficient management of electricity systems.

2.1.2 THE DEMAND: ELECTRICITY IN THE HOME

The demand, from houses to industries and transport, remains the driver of production, either from renewables or any other fuels. In the home, the demand – or electricity consumption – is the sum of its appliance consumptions, as defined in Equation (1).

$$Consumption = \sum_{i=0}^n Consumption\ of\ Appliance_i \quad (1)$$

In a typical house *without* solar PV (**Figure 2-4a**), electricity consumption equals the amount of electricity *imported* from the electricity grid. However, in a house equipped for domestic electricity generation, a complex set of flows of electricity are introduced:

1. Generated electricity: The amount of electricity produced through the property's solar panels. The household may receive payments for generating renewable energy.
2. Imported electricity: The amount of electricity imported from the electricity grid to the home because the household is not generating enough of its own power to meet its demand. This electricity is purchased from an electricity supply company in the same way as a typical house without PV.

¹⁵ International Energy Agency (IEA) – Smart Grid roadmap 2011 (p.6)

¹⁶ DECC – Smart Metering Implementation Programme

3. Exported electricity: The amount of electricity generated by the property in excess of the household's immediate consumption. The power cannot be stored and is sent to the grid. The household may receive payments for exported electricity.

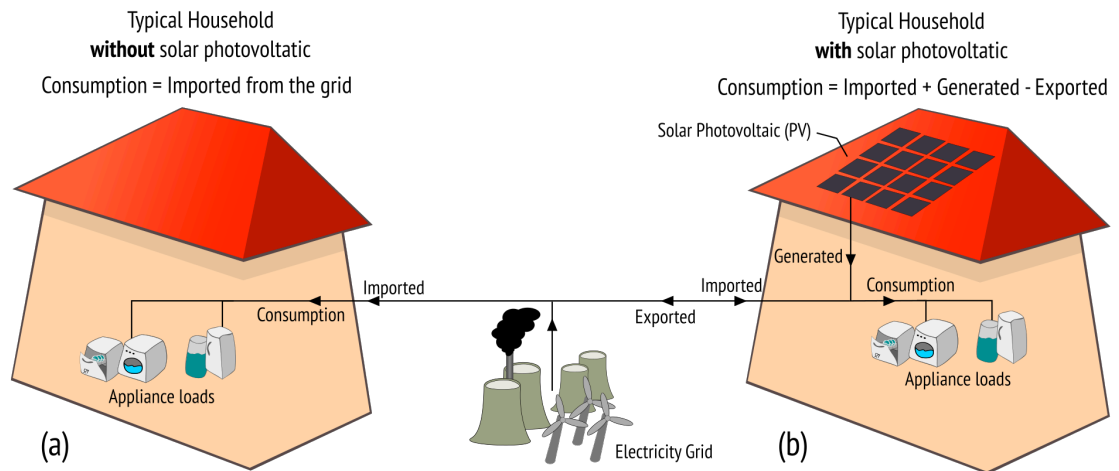


Figure 2-4 Electricity relationship in typical household. a: without solar PV, b: with solar PV

As a result of this complex electricity relationship, the consumption of a typical household with solar photovoltaic is:

$$\text{Consumption} = \text{Imported} + (\text{Generated} - \text{Exported}) \quad (2)$$

Figure 2-4b shows this relationship. In that context, residents can use electricity they produce through their solar panels to power their appliances. We call this process *self-consumption*. They could store excess electricity in batteries, although this is extremely rare today. Finally, they can export the surplus to the electricity grid, but this process includes losses through the transport of electricity (as mentioned above, more important at the distribution stage). It is important to notice micro-generation cannot be exported beyond the micro-grid (the local distribution network). In a scenario of a residential area in which most roofs would be covered with solar PV generating power simultaneously, exporting power in the middle of the day would threaten the local network as everyone would be producing but not consuming.

Domestic electricity consumption is not evenly distributed throughout the day, peaking in the morning and in the evening. While the consumption of an individual house is low, the sum of all the houses has a significant impact on the whole electricity network. For example, evening television advertisements are well-known events generating a high peak of consumption, called ‘TV pick-up’¹⁷ when everyone is rushing into the kitchen

¹⁷ Can you have a big ‘switch off’? (BBC News, 6/09/2007) http://news.bbc.co.uk/2/hi/uk_news/magazine/6981356.stm (accessed on 16/09/2015)

to turn on the kettle. These peaks of consumption make the electricity more carbon intensive, as we saw in the description of the electricity grid.

In the UK, generating households generally consume more electricity than they collect through their solar panels. As a result, they have to import electricity from the grid. **Figure 2-5** illustrates these challenges and highlights that local solar electricity generation and householders' consumption are out-of-sync (fictitious data, see Chapter 5 for actual chart). Green represents consumption of solar electricity, red is power imported from the grid. The remaining part, in blue, is solar electricity exported to the grid.

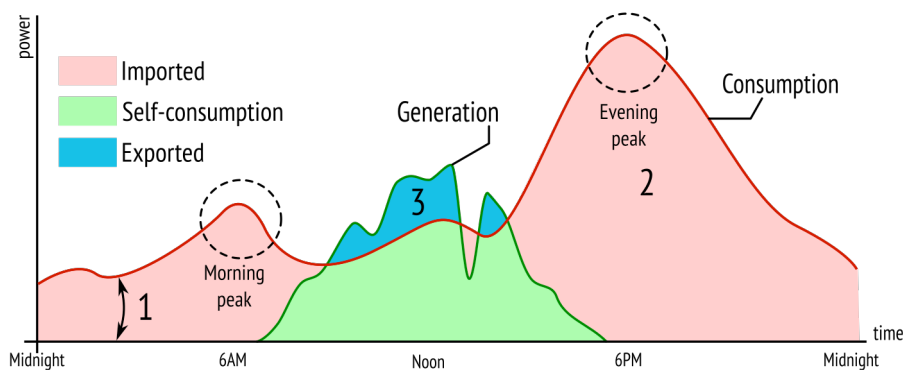


Figure 2-5 Electricity consumption and solar electricity generation of a typical household with solar PV over one day. 1: General need to reduce the consumption; 2: the domestic consumption shows sharp peaks during the morning and the evening; Since solar electricity generation and electricity consumption are out-of-sync, renewable energy is not consumed locally. Notes: this chart relies on fictitious data to ease the explanation. Actual consumption and generation data are presented in Chapter 5.

The tariff to buy electricity from the grid is either set at a fixed price, or, as it is increasingly the case, it is variable in an effort (by electricity companies) to influence the consumption at peak times. For instance, in the UK the 'Economy 7' tariff offers two different tariffs: one for daytime, another (cheaper tariff) for night-time. In the near future, Real-Time Pricing systems (RTP) and smart metering will allow new tariffs to be applied as regularly as every hour or less (Allcott, 2009). Some electricity providers propose a green tariff that guarantees green fuel of each kilowatt-hour bought from the grid. They make sure to produce or buy enough electricity from renewables to match their demand. However, as argued earlier, matching the overall supply of green electricity with demand is not enough: it does not prevent households from consuming carbon intensive electricity when there is a grid-wide high demand or a tiny green supply.

Following the presentation of the electricity grid, this section introduced domestic consumption, generation and the exchanges with the grid. It highlighted the complexity of the domestic electricity system and how it fits in and influences the entire network.

2.1.3 DISTRIBUTED GENERATION: THE CASE OF SOLAR PV

Today, householders can also produce electricity and sell it to the grid. Electricity generated through solar PV does not emit CO₂ and thus helps to preserve the environment. However, sunlight is a periodic source of energy which implies that solar PV can produce electricity only during daytime. Furthermore, similarly to wind generation, solar generation is dependent on multiple parameters including the weather, as well as diverse obstacles making shadows on the solar PV (e.g. trees). We already highlighted the contrast with historical electricity power plants such as coal or nuclear: the amount of electricity generated through solar PV is variable. This is not only during the day, but also from one day to another with some countries (including the UK) experiencing huge seasonal variations.

Solar PV installations account for the majority of domestic generation. As shown in **Figure 2-6**, the British installed capacity of solar generation went from near zero in 2010 to 3GW in 2015^{18,19}, which doubled over the course of this PhD, between 2012 and 2015. During the same period, other domestic generation technologies progressed very slowly. This trend has not been impacted by the reduction of government subsidies. By 2016, overall electricity generation from solar (domestic and commercial) is expected to reach 55GW in Germany²⁰. This upward trend is a motivation to investigate the effective management of domestic solar electricity generation. Current government policy is for the UK to produce 15% of its electricity from renewable sources by 2020 (DECC) which should drive further increases in domestic generation.

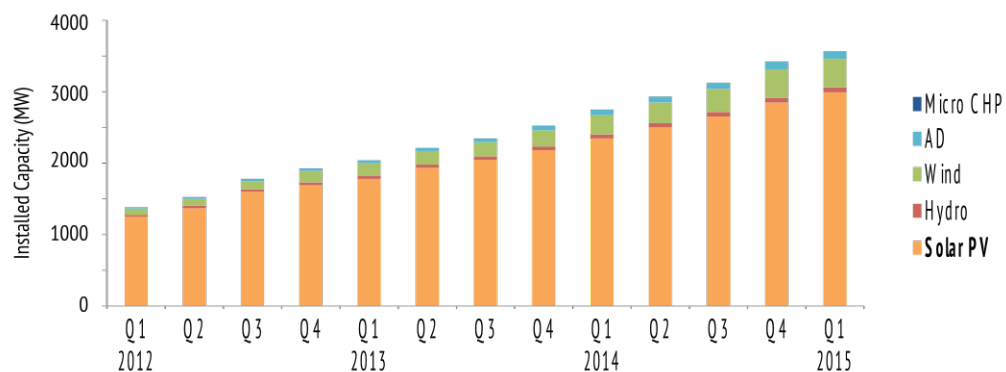


Figure 2-6 Installed capacity under Feed-in Tariff contract. This graph displays the eligible installed capacity¹⁸, in Great Britain, between 2012 and 2015¹⁹ (MW)

We note this installed capacity of solar PV (3GW) is lower than the estimation at peak generation time in **Figure 2-2** p.11 (around 5.8GW) because it only includes installed (mostly domestic) capacity under a Feed-in Tariff (FiT) contract (excluding installations greater than 50kWp in the UK). To encourage the use of solar

¹⁸ Solar generation from installations that received Feed-in Tariff generation payments are typically domestic installations.

¹⁹ Source: GOV.UK, Energy trends section6: Renewable – 25/06/2015 (Department of Energy & Climate Change)

²⁰ Federal Ministry for the Environment, Nature Conservation and Nuclear. Development of renewable energy sources in Germany in 2012

PV governments around the world subsidise domestic electricity generation through FiTs, yet each FiT system varies widely from country to country. **Figure 2-7** illustrates these variations – and complexity – across the UK, Germany and France. In the UK, most of the financial benefits of the solar PV come from the generation, while exporting (selling) to the grid pays less than the cost of importing (buying) from the grid. Thus, it promotes self-consumption. In Germany the formulation is different but the result is similar: the closer the consumption is to the local generation, the higher the benefits are. The French model contrasts with the two others. The financial benefits coming from the solar PV rely on the export to the grid, which is paid higher than the cost of importing from the grid. As a result, there is no financial interest in France for increasing self-consumption.

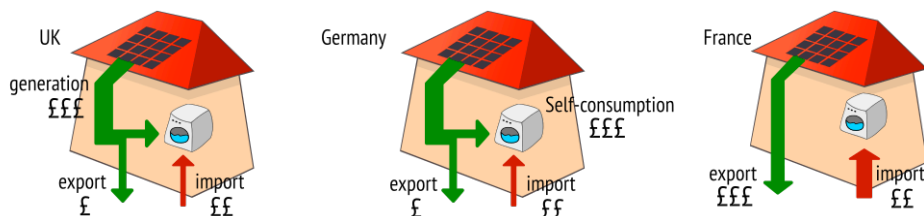


Figure 2-7 FiT policies in the UK, Germany and France.

In summary, government targets and the reality of the market highlights the increasing development of solar PV technologies today and for the coming years. We see that most FiT policies, though difficult to understand, are designed to encourage self-consumption. We now have an overview of the electricity system from the grid to the house with distributed generation. We are now in a position to formalise three important concepts: the net cost, the carbon intensity and the energy efficiency.

Net cost

We use the net cost to evaluate the *economic* characteristics of the domestic electricity system. This represents the final electricity bill the householder has to pay. In the context of domestic electricity generation, the net cost includes the cost of imported electricity and considers the payments received relating to generated and exported electricity depending on the national policy. For UK households we saw that the best strategy is to maximise self-consumption, i.e. minimising imported and exported electricity.

Carbon intensity

Throughout this section we used carbon intensity to show the direct *environmental* impact of electricity. We emphasised the challenge of electricity generation from uncontrolled renewable sources, how these can destabilise the grid and push for high carbon generation as backup. The best strategy is again to maximise self-

consumption. This reduces the import of carbon intensive electricity from the grid while minimising the export of uncontrolled generation into the grid.

Energy Efficiency

The efficiency of the system represents the amount of electricity lost between supply and demand. We highlighted the significant energy losses implied by the transport and transformation of electricity. Most of these energy losses happen at the last step: distribution. Maximising self-consumption, i.e. minimising the export of electricity coming out of solar PV is the best strategy for an efficient consumption.

2.1.4 SUMMARY: MINIMISING IMPORT AND EXPORT

The grid mix varies over time and is depending on the location. Conventional fuels such as coal and gas emit large amounts of CO₂ in contrast with nuclear and renewable energy. However, their production can be used to react quickly to and maintain the balance between supply and demand. In contrast, nuclear cannot be adjusted quickly and most renewable energy cannot be controlled, threatening sometimes the stability of the electricity network. Finally, the transport from the producer to the consumer generates transmission and transformation losses. In conclusion, the best place to use renewable energy technologies is on the production site, avoiding transport losses and the impact on the rest of the grid. Thus, the technical optimisation of domestic electricity with micro-generation in the UK can be summarised as **minimising the import from and the export to the grid**. In the next section we define and motivate the Demand-Shifting mechanism as a key element of this optimisation.

2.2 DEMAND-SHIFTING

The global objective is thus reducing electricity both imported from and exported to the grid. In this section we define and motivate the idea of a Demand-Shifting mechanism to address this challenge.

2.2.1 DEFINITION

Pierce and colleagues conducted in-home interviews and an online survey about everyday interactions with energy-consuming products and systems in the home (Pierce, Schiano, & Paulos, 2010). They propose a new terminology referring to a range of sustainable energy behaviours in everyday life:

- Cutting – powering off or putting in an extremely low-power state, e.g. powering off the television
- Trimming – using a ‘lower’ setting when using a product, e.g. washing clothes on ‘cold’ rather than ‘hot’ temperature wash cycle.

- **Switching** – using a more energy-efficient product in place of product with similar but different functionality, e.g. using a ceiling fan instead of an air-conditioner.
- **Upgrading** – acquiring a more energy-efficient product to replace a product of the same type.
- **Shifting** – shifting use to a different time or place without necessarily reducing the total energy consumed by that product, e.g. washing clothes during off-peak consumption hours.

Most of these energy behaviours involve direct actions by the householders. The main area that computer science can contribute to is that of energy shifting. The concept of energy shifting refers to using an appliance during a ‘better’ period of time. We see two research opportunities: (i) generated electricity can be stored and used during electricity consumption peak-times – or (ii) electricity demand can be postponed to a better electricity generation period – such as a sunny period providing solar electricity generation. These are two new opportunities for sustainable electricity use without electricity consumption reduction.

Matching the Demand through Energy Storage

Crespo Del Granado and colleagues proposed a domestic energy management system focusing on local storage (Crespo Del Granado, Pang, & Wallace, 2014). Their system produced local electricity through a wind turbine and local heat through rooftop solar thermal panels. It can also store energy – electricity in batteries and heat in a hot water tank. Their results showed electricity cost savings for the householder up to 50% using affordable lead-acid batteries compared to a house without local generation. They further argue that batteries increase the use of local energy generation by 20%, showing that energy storage has a role to play in domestic energy management and energy demand-shifting.

However, the electricity storage process incurs energy losses and given the price of batteries remains an expensive option for individual household. McKenna and colleagues present the economic and environmental impact of the use of lead-acid batteries in grid-connected PV system. Based on three models of battery and the current cost and subsidies, they highlight that the return on investment for an individual house is negative (McKenna, McManus, Cooper, & Thomson, 2013). However, the recent penetration of electric vehicles (EVs) on the market has pushed the development and production of Lithium-ion batteries.

Tesla, a leading EV manufacturer, is currently in the forefront of this rapidly growing market of electrical storage with batteries for EVs. These batteries are also designed for a domestic setting and the enthusiasm for these technologies is driving the prices down²¹.

Postpone the Demand to a Better Electricity Generation Period

A different approach is to look at the domestic energy demand and to shift consumptions that are flexible in time towards a better period. The literature also refers to ‘load shifting’ as a mechanism that aims to move the electricity load from the consumption peak hours (**Figure 2-5** (2) p.16) to off-peak hours of the day. In this thesis we use Demand-Shifting, considering the ‘electricity demand’ as the interplay between householders, devices and the environment at a given time rather than directly the decontextualised electrical ‘load’. In the UK, Demand-Shifting first appears in 1952 with the introduction of the day and night tariffs standard for domestic, commercial and farm consumers (The Electricity Council, 1987). The Electricity Council explains that ‘*Cheap night rates served to flatten the load curve thereby improving the use made of the system*’. Today, this is the *Economy7* tariff we presented in section 2.1.2. Such tariffs allow householders to use simple solutions such as time switches, for example, in order to allow their hot water heater to be turned on only during the night to benefit from the cheaper tariff.

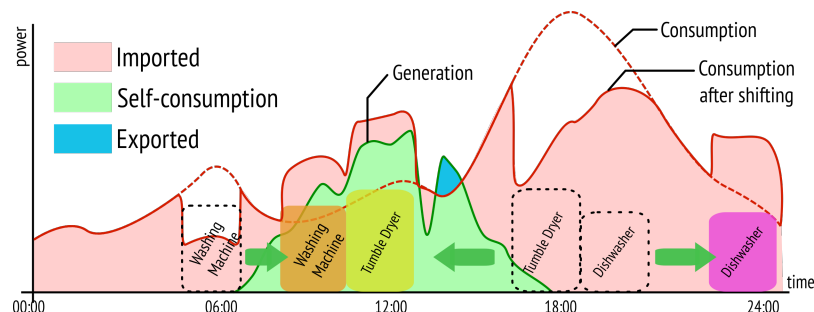


Figure 2-8 Demand-Shifting of interactive appliances such as the washing machine. Built on fictitious data, this chart illustrates the impact of time-shifting appliances from an original time (dashed rectangles) to a better time (coloured rectangles) on the overall consumption.

A largely underexplored area is how the idea of delaying electricity consumption relates to the context of local solar electricity generation. **Figure 2-8** goes back to the fictitious generation and consumption curves presented in **Figure 2-5** p.16 to illustrate the Demand-Shifting with a washing machine, a tumble-dryer and a dishwasher. The washing machine load is postponed around of few hours, catching solar power early morning, while the best time for solar energy is booked for the dryer: the biggest load. It is not worth pushing the dishwasher load forward as there is not much generation. Furthermore, it likely requires the end of the dinner before starting the dishwasher. The load could then be postponed to run at night.

²¹ Elon Musk's big announcement: It's called 'Tesla Energy' – Business insider UK, 1/05/2015 – <http://uk.businessinsider.com/here-comes-teslas-missing-piece-battery-announcement-2015-4?r=US&IR=T> (accessed on 16/09/2015)

Opportunities for electricity Demand-Shifting in the context of solar electricity generation have already been highlighted as a solution that could increase the use of solar electricity by 20% (Bahaj & James, 2007). Although this estimation is a purely mathematical approach and may not have taken on board all the social complexities, it does highlight the potential impact of electricity Demand-Shifting.

While in the long term both energy storage and Demand-Shifting options will be required for a sustainable energy management, this thesis focuses on the demand. In the next section we present the motivation to focus on Demand-Shifting in the context of domestic micro-generation.

2.2.2 MOTIVATION

Building on the definition of Demand-Shifting, this section presents the motivation leading to focus specifically on Demand-Shifting in the context of micro-generation with a trigger, an opportunity and a research gap.

The Trigger: Micro-Generation

Adoption of domestic micro-generation is still relatively low and not much is known about why households choose to buy them, what households think about producing their own electricity, and how they perceive them. While we highlighted the growing installed capacity of solar PV in Section 2.1.3, it is important to note that it still represents a few households. A 2006 study by the Open University on the drivers for adoption of micro-combined heat/power systems (before feed-in tariffs came into effect) uncovered that for users of solar PV environmental concerns topped the agenda. A significant proportion of the respondents mentioned ‘pleasure of using a renewable energy’ (31%) (Caird, Roy, & Herring, 2008). Similarly, Bergman and Eyre (Bergman & Eyre, 2011) discovered that environmental concerns are the main motivation for adopting PVs or micro-wind turbines. Some households’ adoptions represent a way to reduce fossil-fuel use. For others, this investment is symbolic and provides a way to display environmental consciousness or to set an example. For still others, adoption is a protest against ‘the system’, or a step towards self-sufficiency (Woodruff, Hasbrouck, & Augustin, 2008). Conversely, some households reject micro-generation installations because of financial considerations, respect for neighbours who might object, and/or difficulties finding an appropriate site.

The Opportunity: Emerging Behaviour

Domestic electricity generation is a new method to produce electricity but it is also an opportunity to make electricity more concrete in everyday life. In contrast with the concept of unlimited electricity we have had for

decades, solar electricity generation is collected in small quantities and during a limited period of the day that is difficult to predict, especially in the UK. Bringing the production close to the consumption creates new opportunities to make people understand electricity as a limited resource. It is a new way of ‘materialising energy’ (Pierce and Paulos 2010). In 2004 the Green Alliance’s Micro-Generation Manifesto (Collins, 2004) argued that the small-scale nature of micro-generation means that individuals can play an active part in attaining the UK’s environmental goals:

‘Micro-generation will make the public co-producers of climate change solutions rather than passive consumers of energy, helping to combat the ‘what can I do?’ apathy that undermines so many well-meaning public education campaigns’ (Collins, 2004)

Indeed, the literature provides evidence that micro-generation technologies encourage energy efficient behaviour.

Keirstead presented the concept of the ‘double dividend’ for domestic energy generation (Keirstead 2007). He explained that energy micro-generation – energy produced locally such as through solar panels – and the sociotechnical system including regulations, electricity tariffs and metering technologies have a high influence on residents’ behaviour and how micro-generation households are incorporated into the electricity system. He describes micro-generation as delivering a ‘double dividend’ – that is, not only does micro-generation produce renewable energy but it also changes residents’ behaviour, giving rise to reduced electricity consumption. It encourages households to reduce their overall electricity consumption by approximately 6% beyond the solar savings and shift demand to times of peak generation. He highlighted that some households with micro-generation engage in Demand-Shifting.

A UK study (Willis & Munro, 2008) observed that 88% of consumers who installed micro-generation found that household behaviour was significantly altered to reduce energy consumption after installation (including lifestyle changes as well as traditional energy saving measures).

In a report, Dobbyn and Thomas look at how micro-generation affects attitudes and behaviour around energy (Dobbyn & Thomas, 2005). They looked at how people’s relationship with energy and their motivations to be energy efficient varies whether they have micro-generation or not. They conducted 29 in-depth qualitative interviews across UK including 13 households actively involved in micro-generation uptake, 9 households living in social housing where the local authority had installed renewable technology and 8 mainstream households without micro-generation. To compare these categories of households, they define the term

‘energy self-efficacy’, a measure combining the level of energy awareness with the level of energy consumption concern. They highlight that none of their mainstream interviewees could be described as having energy self-efficacy, taking their energy for granted, rarely thinking about energy and not making strong link between their usage and costs. In contrast, most of the households with micro-generation had developed a strong awareness about their energy and the link between usage and generation. However, not all of the social housings provided with renewable energy exhibited a shift in understanding and behaviour, suggesting that the technology alone is not enough. These households exhibit evidence of energy efficiency behaviour change empowered by a more tangible energy and feeling good and proud about their technology. The authors highlighted a heightened energy consciousness among these consumers, even those merely in contact with micro-generation:

‘Beyond the sheer excitement and pleasure of DIY energy generation, the impact is seen in householders’ shifting attitudes to energy conservation and consumption ... there starts to develop a strong sense of which behaviours are free and self-provided, versus ones that cost money and are supplier-dependent.’ (Dobbyn & Thomas, 2005, p. 6)

Keirstead’s study (Keirstead, 2007) states that *‘micro-generation provides a tangible hook to engage householders emotionally with the issue of energy use’*. The emotional resonance appears to be connected to the *‘sheer pleasure of creation and of self-sufficiency’* reported by participants.

These findings are in agreement with work by Hondo and Baba who reported on similar energy behaviour changes through a questionnaire survey of 200 Japanese households with solar PV in 2004 (Hondo & Baba, 2009). They suggest that solar PV awareness increases concern and knowledge about the environment and highlights the need for further research in that direction. The authors also noted an increased level of communication about energy within these households. In the Netherlands, a study by Derijcke and Uitzinger (Derijcke & Uitzinger, 2006) combined two surveys of over 80 households – at the point when they have just bought solar PV and after 3 years – and the monitoring of overall consumption of four households. It highlights that participants shifted 15% of their washing machine, dishwasher and dryer loads from night to day times. Participants were using their generation meter to do this process manually and their motivation was reported to be more environmental than financial.

Research Gap

The reported behaviour changes, especially those related to purposeful Demand-Shifting, are surprising given the lack of concrete information people have about their own electricity generation. As indicated above, even

with currently available energy monitors, the generated energy is essentially invisible to home occupants. Users ‘experience’ the energy primarily through a lowered energy bill (only by manually comparing bills for the same period one year after installation). The problem is that consumers who want to shift their demand in time have no data to base their decision on. Thus they are left to guess the relationship between demand and supply.

As we will emphasise when describing the eco-feedback approach in the Section 2.3.2 (p. 29), energy demand reduction and behaviour change have been linked to energy feedback systems, such as smart meters or in-home displays (Darby, 2006). Early studies have speculated about potential synergies between feedback and micro-generation (Eyre, 2004) and households seem to express a desire for energy monitors that show consumption and production (Pierce & Paulos, 2012). However, we have no real understanding about the link between micro-generation, feedback and behaviour change. This research aimed at addressing this research gap. The next sections present both the mechanism and existing approaches to Demand-Shifting.

2.2.3 SUMMARY: NEEDS FOR A DEEPER DEMAND-SHIFTING INVESTIGATION

In this section we defined the Demand-Shifting mechanism as an opportunity to reduce the energy gap. We highlighted early evidence of natural engagement into manual Demand-Shifting in the context of domestic solar electricity generation. While the concept of shifting electricity consumption was introduced several decades ago, the Demand-Shifting mechanism in the context of micro-generation is new, representing concrete opportunities for householder engagement. However, current evidence needs to be corroborated and a set of three questions need to be addressed in more details to measure and seize these opportunities:

1. How do householders connect their micro-generation with their consumption, and hence with their daily activities? How does manual Demand-Shifting take place? How much effort and what conditions does it require?
2. While we reported on several studies highlighting the potential of Demand-Shifting, there are no studies weighting the social cost and evaluating precisely the potential of this mechanism. What are the constraints and difficulties of shifting the time of activities? What are the financial, environmental or social benefits and drawbacks?

3. How can we support the initial impulse coming from the micro-generation context without losing householder's engagement? Can we recreate these favourable conditions for households without micro-generation?

In this thesis we provide initial answers to these questions through the studies that we carried out. The next section we present the existing approaches to the Demand-Shifting mechanism, highlighting the wide flexibility of its implementation through Demand Response, eco feedback and recent supportive tools.

2.3 APPROACHES TO DEMAND-SHIFTING

Earlier, we provided the definition and the motivation for Demand-Shifting. In this section we review existing research approaches that have implemented various forms of Demand-Shifting in order to highlight their strengths and weaknesses and situate our own research in the literature. First, we detail approaches that aim to automate the energy management system, hiding the energy problem to the user. Then, we move towards user-centric solutions that rely on the user to perform actions in order to save energy. Finally, we cover a few interactive systems that aim to combine automation and user interaction to support householders towards their goals. Each approach is presented through the following criteria:

- Objective – Are they aiming to:
 - reduce the electricity consumption?
 - reduce the cost for the energy provider or the cost for the householder?
 - reduce the environmental impact through energy efficiency or carbon intensity?
 - reduce the disruption for the householder?
- Algorithm – Does the Demand-Shifting mechanism
 - include a reactive process, taking decision and action in reaction to an event?
 - include a predictive process, anticipating future events?
 - include a search for optimisations such scheduling?
 - include the users-in-the-loop, letting them know what is happening? Letting them decide what to do? Supporting them through decision and action?
- Implementation – Do evidence and contributions supporting these approach
 - rely on models or simulations?
 - rely on empirical quantitative or qualitative data analysis?
 - rely on prototyping and in-the-wild intervention?
 - rely on the analysis of commercially available products?

2.3.1 DEMAND-SIDE MANAGEMENT FROM THE GRID

In section 2.1.1 p.13, we briefly introduced the Smart Grid, an updated electricity network relying on smart meters to connect each ‘agent’ of the grid, such as power plants, transformers, buffers and consumers through (near) real-time communication allowing the optimisation of the system. In 2010, Farhangi presented the main ingredients to tend towards the Smart Grid, promoting Demand-Side Management (DSM) and Micro-Grid (Farhangi, 2010). DSM includes Demand-Shifting and any mechanism that aims to tune the electricity demand towards a more efficient use of the grid.

A common approach to DSM relies on Dynamic Pricing. Following the principle of the Economy7 tariff (2.1.2), the rate of electricity is variable in order to daunt electricity consumption at peak time and promote electricity consumption at off-peak time. However, Dynamic Pricing could change the rate of electricity as frequently as every 30 minutes. Thus, a range of Demand Response (DR) mechanisms have been explored to automate home appliances in order to respond to such price signal and minimise the cost for the householder. For example, Weng and colleagues presented a smart plug. Placed between the appliance and the power outlet, this device enables appliances to understand and react to DR mechanisms including on and off control and priority management (Weng, 2011).

In a review, Haghighi and Krishnaswamy highlight energy policies, technologies, challenges and opportunities (Haghighi & Krishnaswamy, 2011) of such mechanism. They argue that with DR based on Dynamic Pricing, *‘control actions are solely implemented based on the supply conditions and regardless of the consumer’s current situation’*. They suggest that context-awareness could be a potential solution to this issue. In fact, this mechanism looks at the electricity problem from the grid point of view. Consequently, it misses two important the local dimensions:

1. First, Dynamic Pricing does not include local energy generation. As emphasised throughout the Section 2.1, the role of micro-generation is a key element of the Smart Grid and its efficient use relies on local management.
2. Second, interactive appliances such as washing machines, clothes driers or dishwashers require user intervention before they can be used – such as changing between operating programmes, or adding washing and soap.

Thus, we focus the remaining of this section on projects that articulate DSM systems, paying close attention to these local dimensions. Zhu and colleagues present a system architecture taking account of both local

generation and grid condition through dynamic tariffs (Zhu, Tang, Lambbotharan, Chin, & Fan, 2012). They implement an Efficient Control Algorithm which aims to minimise grid power costs – the cost that households pay for importing electricity – based on an effective management of domestic electricity, i.e. optimising the combination of generation, consumption, storage and tariff of electricity. A simulation is used to evaluate the algorithm and results show that the grid power cost is reduced by 37% compared to the use of renewable energy without Efficient Control. This project shows the potential of effective domestic electricity management and therefore the potential of domestic electricity Demand-Shifting. In Ireland, the grid relies on significant electricity generation from wind energy (Finn, O'Connell, & Fitzpatrick, 2013). Finn and colleagues focused on the dishwasher to evaluate the potential of shifting consumption towards periods of high wind generation. They monitored a dishwasher over six months and asked participants to record after each load the time at which the dishwasher was open for the first time. They consider this time as the deadline to which the dishwasher's load has to be completed. Looking at different objective such as minimising the cost, maximising the demand on wind generation or minimising associated carbon emissions, they highlight potential cost saving of 21.1%.

Another project motivates the need of a closed relationship between a smart home and a smart grid (Kamilaris, Tofis, Bekara, Pitsillides, & Kyriakides, 2012). The authors highlight the need of smart home energy-aware systems to take account of the grid conditions and dynamic prices, not only to make local decisions, but also to intelligently control the use of household electrical appliances and therefore save energy and money. They applied their model to a DR mechanism; starting a washing machine based on a dynamic tariff. Although this project did not consider all the social complexities of 'auto-start' washing machine, it did consider appliances which require resident intervention as a potential electricity Demand-Shifting.

While we emphasised the lack of local resource consideration in system relying Dynamic Pricing in these latest projects, we also motivated the need to look at the macro environment throughout the Section 2.1. At the University of Twente, Molderink and colleagues looked at DSM with an interesting compromise from the micro-grid point of view, managing domestic generation and storage in a three-step process (Molderink, Bakker, Bosman, Hurink, & Smit, 2010). First, the system predicts the availability of local resources for each household. Then a resource planning is built at micro-grid scale, producing a signal comparable to a local Dynamic Pricing system. Finally, the schedule of appliances is computed for each house. This project

emphasises prediction, scheduling and communication requirements for the Demand-Shifting mechanism that take both micro and macro dimensions into account.

In this section we presented top-down approaches to the Demand-Shifting mechanism, relying on macro environment signals such as the Dynamic Pricing in order to control domestic appliances. We highlighted the lack of consideration for local resources and householders' needs and constraints. Finally, we showed an opportunity for combining micro and macro objectives. In contrast, a different approach to DSM might be increasing the users' awareness, trying to drive their energy behaviour.

2.3.2 ECO-FEEDBACK: DRIVING BEHAVIOUR CHANGE

The relationship between residents and energy in the home is complex. Energy is invisible, intangible and difficult to understand. Pierce and Paulos depicted how people have difficulties understanding energy (Pierce & Paulos, 2010). People refer more easily to a physical action, such as applying a force, as something much more concrete. Electricity, an already complex concept, becomes even more difficult to understand by adding generation and storage in the system. Electricity feedback or *Eco-Feedback* relies on increasing people's awareness about energy, assuming that this will help them reduce their overall electricity consumption.

Resource Man

Computer displays are widespread in everyday life and home is no exception, with In-Home Displays (IHD) showing graphs and diverse values. Despite these devices being designed for domestic use, Strengers mentions that householders express difficulty understanding data provided through their IHD (Strengers, 2011), and sometimes they misunderstand these data resulting in behaviour that adversely impacts energy consumption. Despite these negative points, studies have shown that energy feedback savings range from 5% to 15% of energy (see (Darby, 2006) for a review). Thus it is important to find out what type of energy feedback is effective. Fischer conducted a review (Fischer, 2008) to determine which type of feedback is the most successful. She extracted five key points:

1. Appliance-specific breakdown;
2. Computed and customised;
3. Interactive and engaging;
4. Often; and
5. Over a long period.

She also learned how households prefer their feedback. Among the propositions, Fischer mentions that people are interested in comparisons of information they can understand; requiring clear indications, common-sense labelling, and explanation. However, Fischer observed that preferences are different between countries.

Strenger (Strengers, 2014) discusses the direct transfer of energy management from energy utilities to the householders with the growing of smart meters and local generation. She refers to the ‘Resource Man’ as ‘*the ideal of a data-driven, technology-savvy home energy manager who is interested in, and capable of making, efficient resource-management decisions*’. In order to mitigate this effect and take more of the household’s context into account, she emphasises two directions of research to focus on:

- Supporting the ‘mess’ of householder’s everyday life, looking into daily routines to have a sense of their concrete home environment.
- Designing for others to widen the energy audience. Existing work lacks opening to the rest of the householders.

In this thesis we explore the Demand-Shifting mechanism in line with a particular attention to these directions.

Widening the Audience and the Objectives

Ambient displays have also been explored as methods to provide energy feedback. This new form of feedback allows blending energy awareness in everyday life. **Figure 2-9a** shows the Power Aware Cord, making the electricity visible by lighting a power cord (Gustafsson & Gyllenswärd, 2005).

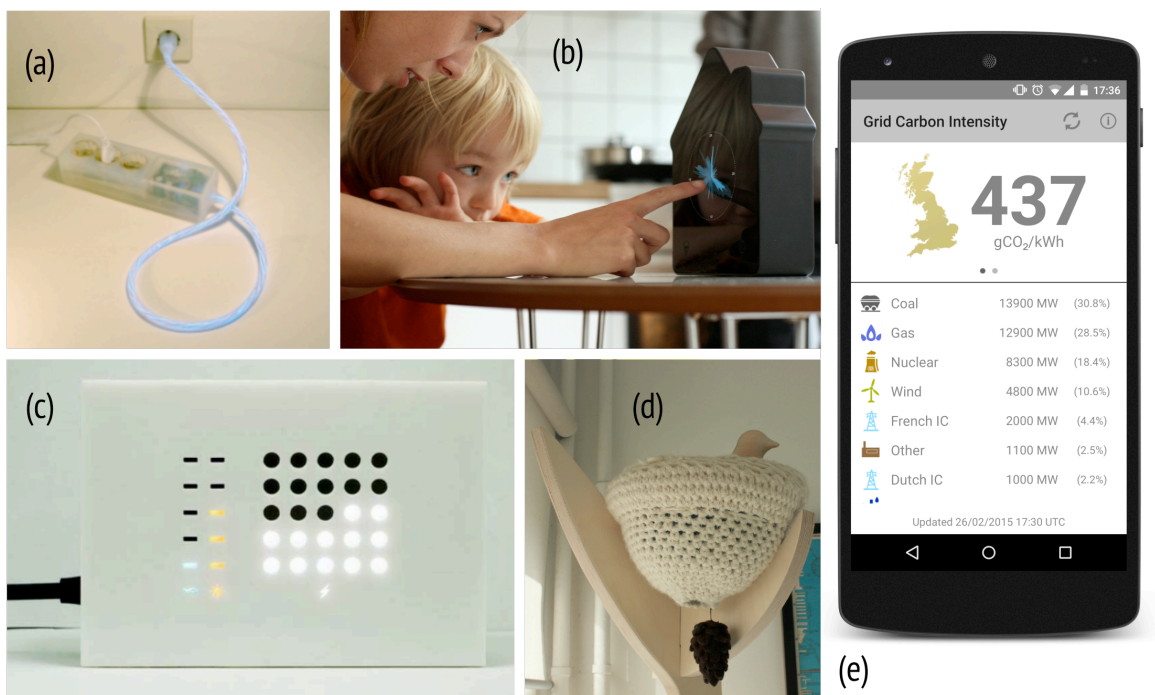


Figure 2-9 Eco Feedback literature. a: the power cord (Gustafsson & Gyllenswärd, 2005); b: the energy clock (Broms, et al., 2010); c: the local energy indicator (Pierce & Paulos, 2012); d: the Peacetime tree (Wessman, Colombo, & Katzeff, 2015), e: the Carbon Intensity Application²²

Figure 2-9b illustrates the energy clock providing the last hour's or day's worth of electricity consumption, an object that we can look at like a kitchen clock (Broms, et al., 2010). Both technologies make the concept of energy more visible to the resident. Wessman and colleagues go beyond the visual and energy consumption dimension. The Peacetime tree prototype (**Figure 2-9d**) use bird sound and smell to notify a peak time of consumption (Wessman, Colombo, & Katzeff, 2015). In contrast with other approaches stressing high tariffs and consumption, this project aimed to convey the idea that it is time to relax, and that we can switch off our appliances to enjoy bird song – thus reducing consumption through a different type of motivation.

Until now, electricity feedback focused mainly on electricity consumption rather than the electricity generation. A review of over 50 recent HCI publications details opportunities in domestic energy design based on emerging energy systems such as smart grid, smart meters, Demand Response and Distributed Generation, which have been detailed in the previous section (Pierce & Paulos, 2012). The authors highlight opportunities to support behaviour change by increasing awareness of these emerging energy technologies. First, they suggest more visualisation of energy sources to inform about the carbon intensity of the consumed electricity, through increased visibility on Dynamic Pricing and availability of electricity coming from renewable sources. Second, beyond conservation behaviour they promote energy shifting and sharing behaviours has ways to use energy differently and more intelligently. Finally, beyond per-appliance electricity consumption data that are displayed on a centralised screen, appliances could be redesigned to provide energy awareness themselves. For example, washing machines could be designed in order to promote sustainable behaviour by selecting low energy programme by default.

Following their own conclusion, Pierce and Paolo proposed the Local Energy Indicator (see **Figure 2-9c**) (Pierce & Paulos, 2012). This ambient display shows the current local electricity availability from the wind and the sun. A different approach is that by Rogers and colleagues²² focusing on an application for grid energy feedback, providing instant electricity generation values by fuel (coal plant, nuclear plant and so on). This Smartphone application (see **Figure 2-9e**) makes people aware of the source of the current electricity generation in the United Kingdom. This information is important to decide when would be the best period to consume electricity and can help people make decisions on appliances' start times. However, it is difficult to

²² GridCarbon application: <http://gridcarbon.uk/>

understand for typical users: it provides a single number – the carbon intensity in grams of CO₂ per kilowatt-hour (gCO₂/kWh) – and provides no comparison to understand this value.

Froehlich explored how HCI can motivate behaviour change and produced ten design dimensions (Froehlich 2009). Among them, units of measurement, such as kWh or kg CO₂ that are often hard to understand could be translated into equivalent, but more comprehensible, units such as the number of car trips or number of flights. Recommending action is also a method to change energy behaviour but it has to be adapted to a specific context to be effective. Finally, comparison and social sharing can also support new behaviour following the current social networking tendency. Following Froehlich, Power Ballads is a project that aimed to publish adverse messages about electricity consumption on the social network page of the participants (Foster, et al. 2011). Although this method risks the disengagement of the participants, the results show that participants discuss these messages, but participants would appreciate positive messages as well. Informed by focus groups, Foster and colleagues designed a Facebook application which displays current and historical data with emoticons for the users and a ranking of their friends' energy consumption (Foster, et al. 2010). Results show that these social features may be able to play a role in reducing electricity consumption in the home.

While these last projects open domestic energy management to either more people in the household or more objectives, such as optimising the use of local generation, they still rely on the assumptions the householders:

1. Will parse the eco-feedback information
2. Will be able to implement following actions
3. Will change their behaviour

At the boundary between eco feedback and supportive system, Costanza and colleagues designed 'FigureEnergy' (Costanza, Ramchurn, & Jennings, 2012). This interactive visualisation aims to encourage users to engage with energy by labelling the energy consumption events thus creating a view of the electricity consumption 'per appliance'. This project is still focusing on driving behaviour change, though, 'FigureEnergy' provides support to parse and interact with the energy data while pushing householders to engage. The authors conclude with encouraging results through an in-the-wild trial in twelve households, engaging the users with their energy consumption and leading them to think more about the activity – e.g. doing the laundry or cooking – rather than the appliance.

2.3.3 SUPPORTING DECISION OR IMPLEMENTATION OF DEMAND-SHIFTING

In 1999, Weiser introduced his most famous paper with ‘*The most profound technologies are those that disappear*’ (Weiser, 1999). In contrast, eco-feedback research spent decades trying to make electricity consumption more visible as a way of driving householders towards changing their behaviour. Weiser describes how the designers of window-based interfaces for computer systems back in 90s drove user into the metaphor of the desk – the ‘desktop’ with the bin, the folders, etc. Similarly to this metaphor, eco-feedback tend to force people to reduce their electricity consumption instead of looking at how technology could fit their daily routines to support sustainable behaviours. Moving from the ‘Resource Man’ to a wider audience and multiple objectives requires more supportive systems to take and apply decisions. In this section we highlight existing work that supports Demand-Shifting through user interaction and how a better understanding of the context could help designing this support.

From Demand Response to Supportive Tools

In Section 2.3.1, we described existing work on Demand Response, a mechanism allowing domestic appliances to react to a signal by turning on or off. We highlighted that research in this area focuses on models with assumptions that are disconnected from the actual settings and the reality of the householders. However, it is possible for technology to help householders interact with such mechanisms.

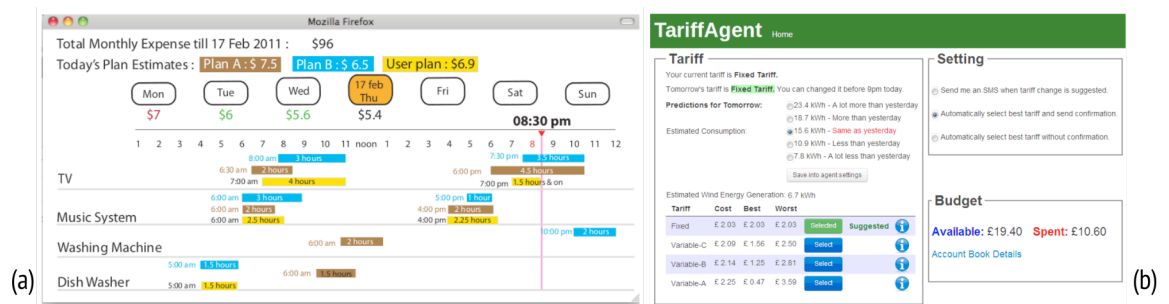


Figure 2-10 Demand-Shifting support. a: the load provisional schedule Yupik (Bapat, et al., 2011), b: the TariffAgent (Alan, et al., 2014)

Yupik is a provisional schedule (see **Figure 2-10a**) suggesting how inhabitants could shift their consumption (Bapat, et al., 2011). The aim of this project was to inform occupants about how they could organise their electricity loads to reduce the electricity consumption peak-time. **Figure 2-10a** shows an example of showing the user three different schedules: suggested plan A (brown) or plan B (blue) alongside the plan that they are actually on that day (yellow). However, three points are missing in this project:

1. The scheduling algorithm focuses on the Dynamic Pricing, thus missing the local generation availability;
2. The display does not allow interaction – i.e. the user cannot select one schedule over another nor receive support to implement one of the suggested schedule
3. The system has not been evaluated, nor is there mention of there being plans to do so in future, so it is not clear how effective this approach would be for actual users.

Alan and colleagues looked at Demand Response and came up with similar conclusions to ours (Alan, et al., 2014). They highlight that most Demand Response approaches focus on simulation, making large assumptions that may not fit with actual conditions that users encounter in their messy home situation. Specifically, it is assumed that energy consumption profiles are predictable, though, as we will highlight in Section 2.4.2, they are actually unpredictable. Furthermore, without a user study, we do not know how much the user would trust such a system in planning loads for the coming days and how much time they would spend to react to real-time electricity pricing. On these conclusions, Alan and colleagues developed TariffAgent, a system supporting the householder to choose the best tariff for the following day and thus evaluate the trust of users in the agent when it may make mistakes. The system relies on electricity consumption monitored in participant's home and predictions. The authors set a scenario where an energy supplier provides a standard tariff for the following day while another supplier relies on wind, with a cheap rate when the wind is blowing and an expensive rate otherwise. In this scenario, TariffAgent has degrees of user interaction that can be configured on a web interface (**Figure 2-10b**):

- Human-guided, the system only notifies the user by text message in case the selected tariff is not considered the best and suggests an alternative. The user can switch tariff by texting back
- Semi-autonomous, the system switches to the best tariff automatically and notifies the user by text
- Fully autonomous, the system switches to the best tariff automatically without notification.

The authors conducted a user study with ten participants who used TariffAgent for 14 days. They report that participants liked the idea of receiving text messages, using them to keep track of the system. They recommend that future agent based system should offer users opportunities to declare their plans and take them into account in the system. Finally, they highlight the need for the possibility to adjust the system's autonomy over time.

In a field study involving ten households, Costanza and colleagues explore a different approach using an agent-based system to help households shift laundry routines based on the electricity tariff (Costanza, et al., 2014). They deployed ‘Agent B’, a prototype system that shows which time-slots will be cheaper and allows householders to book washing machine time-slots. As this was a simulated system, participants received a small budget at the beginning which they could spend as they wished. Participants lived with the system for at least a month. They report that some participants used the tool as a new way to organise their laundry, integrating it with other resources drawn upon to manage the laundry (e.g. social relationships, activities, and the weather). However, other participants struggled to change their habits, keeping their more spontaneous practices. The study suggests increasing user interaction to improve the potential of automated systems. Thus there are opportunities to connect grid objectives with householders. It is, though, difficult to evaluate their potential through only several weeks of study. Longitudinal studies are required in order to collect data for a longer term. Looking at a commercially available product might provide such feedback with real data which would give a more reliable indication of suitability.

Learning from Existing Products

In the Netherlands, Kobus and colleagues investigated how a washing machine that is able to wait for a sunny period impacts on the user (Kobus, Mugge, & Schoormans, 2013). They deployed an Energy Management System (EMS) ‘Smart wash’ from Enexis – a Dutch energy company – in 24 households, all of whom employees of Enexis who had solar PV on their roofs. The washing machine has communication capability, providing the EMS with information and control. **Figure 2-11a** presents a screen example of the EMS controlling the machine. Householders could see the generation forecast over two days as feedforward and to set a deadline for their washing machine load to be done. Then, the washing machine started at the best solar generation period. Based on 21 interviews of these households who had been using the system for three to four months, the authors report that people tended to shift their washing to the peak solar generation period. They also noted that some household members were unable to become interested in the washing machine as a smart appliance with energy saving potential, as doing the washing was not part of their role in the home. Hence the social dynamics surrounding household routines and the division of labour within the home are issues that will impact on the success of new technological approaches to support the change of such routines. The authors recommend that such technologies should integrate feedback with feedforward information, such as prediction, allowing the user to anticipate when the best time would be, but also a reward, such as green

points or financial incentives as indicators of the ‘performance’ and an acknowledgement of the effort this involves.



Figure 2-11 Micro-generation feedback. a: ‘Smart Wash’ (Kobus, Mugge, & Schoormans, 2013), b: the Tiree Energy Pulse (Simm, et al., 2015)

Yang and colleagues (Yang, Newman, & Forlizzi, 2014) compared conventional thermostats with the Nest Learning Thermostat, a commercially available product that learns householders’ preferred temperature patterns in order to automatically optimise the heating system. The Nest is a technology at the boundary between home automation and user interaction, though the objective remains to make thermal control as transparent as possible. The authors studied the impact of the Nest on the user for both short and long terms through a combination of a diary study and 90 initial and follow up interviews. They highlight a short-term engagement that fades off over time, generating trust through a nice user experience but also a limited sustainability. The few interactions with the product led to users not adjusting their schedule, resulting in wasting energy. Building on these findings, the authors draw implications for what they refer to as *eco interaction*, which is about sustaining user engagement while not requiring constant attention.

‘Eco-interaction includes eco-feedback and predictive control, but also includes the design of control interfaces, infrastructures, and basic functionality required to facilitate user interaction.’ (Yang, Newman, & Forlizzi, 2014)

They argue that *eco interaction* should provide optimisation plans that users could easily implement. Such plans should be provided with ‘eco-feedforward’ messages or visualisations showing users the anticipated impact of recommended changes.

Learning from extremes

To understand how to support people in managing energy, looking at extreme cases can help highlighting the issues and how householders deal with them. Banerjee and colleagues looked at how home automation techniques could support householders increasing their use of local generation (Banerjee, Rollins, & Moran, 2011). Their study relies on an off-grid house, a house that is not connected to the electricity grid and

therefore relies on solar energy and batteries. While this type of house represents only a small segment of houses, the authors mention that this population is more enthusiastic and extreme in terms of conservation. It is thus interesting to observe the manual techniques implemented in this context as there is no adoption barrier. The authors fully equipped the house with energy monitoring tools. They came out with three tool suggestions: (i) An early warning allowing the resident to anticipate a level of battery critically low, (ii) advice on the best time to execute high-power tasks and (iii) energy conservation suggestion such as refrigerator temperature. Although these recommendations are mostly designed for off-grid houses, prediction, alert and rescheduling are highly relevant to support householder with solar photovoltaic on their roof. However, a user study is needed to strengthen these design recommendations.

At Lancaster University, Simm and colleagues worked together with inhabitants of Tiree, a small island off the west coast of Scotland. Similarly to Banerjee's research, the 650 inhabitants of Tiree are at the edge of the grid, highly reliant on wind energy to generate electricity and thus interested in optimising their electricity consumption. The authors designed the Tiree Energy Pulse (TEP, see **Figure 2-11b**). In contrast with the previous works looking at individual reward, TEP is designed for a community reward as Demand-Shifting aims to help inhabitants of the whole island getting a reliable electricity supply. The authors report that current synchronisation of everyday life with supply is a form of *opportunistic exploitation* while it could be a *collaborative load management* with the support of the technology (Ferrario, et al., 2014; Simm, et al., 2015). TEP is the result of 8 months of workshops and prototyping engaging communities on the island which highlighted the need for energy forecasting: '*the likely future availability of energy*' (Newman, et al., 2014). **Figure 2-11b** illustrates the prototype showing a 24hrs forecast of energy based on the wind forecast. A little 'tamagotchi' face suggests if the coming 24hrs is the best period of time to consume electricity. The authors report a potential for increasing energy awareness by showing the source of electricity, comparing the electricity consumption to the '*way that meat is bought neatly packed on the supermarket shelf*'. They also highlight many variations between participants and their ability to shift their consumption, because of constraints in a busy household or because of tasks that are not planned in advance.

2.3.4 SUMMARY: PROVIDING SUPPORT BETWEEN MANUAL AND FULLY AUTOMATED

We provided an overview of the three main approaches that connect with Demand-Shifting, highlighting benefits and constraints. **Figure 2-12** presents an illustration of three approaches presented in this section.

While Demand Side Management provides a top-down approach without much control for the householders, eco-feedback relies entirely on the householder's awareness to drive their energy behaviour towards electricity consumption reduction.



Figure 2-12 Illustration of the Automation, feedback and supportive approaches to the Demand-Shifting mechanism.

Supportive tools represent an emerging approach balancing the benefits of Demand-Response and eco-feedback. However, only few recent projects considered supportive tools in the context of domestic micro-generation. This is the research gap addressed by this thesis. In the next section we look at requirements for Demand-Shifting mechanisms.

2.4 DOMESTIC DEMAND-SHIFTING MECHANISM

In the previous section we presented existing approaches to Demand-Shifting, focusing on how and in which context researchers conducted their research as well as their outcomes. We highlighted multiple forms of objectives, algorithms and implementations. Although we observed significant differences between these approaches, there are common steps of what we call the Domestic Demand-Shifting Mechanism:

- First, there is a collection of contextual data to understand what is happening;
- Second, some approaches look ahead, generating prediction to anticipate future events;
- Third, some approaches compute potential improvement
- Finally, throughout the process, householders play a more or less important part of the mechanism.

In this section, we detail each of these four key ingredients of the Demand-Shifting Mechanism, spanning through software engineering and human-computer interaction. We provide an overview of the state of the art technologies and techniques, emphasising that the key components are ready to build a Demand-Shifting Mechanism.

2.4.1 MONITORING: WHAT IS ACTUALLY HAPPENING?

Getting a sense of what is happening relies on the data collected through the monitoring of the home environment. Monitoring is a key part of electricity management in the home as it gives a view on what is happening in the environment in real-time – depending on how frequently we collect the data. Contextual

data allows computers to observe the environment through sensing and metering. From these data we can learn how the system behaves and diagnostic potential optimisations. For instance, we can observe the balance between the household consumption and generation and determine that several appliances are all consuming at the same time. The monitoring provides essential information to take decisions in order to reduce or optimise the energy consumption. However, monitoring is not without its problems and from the literature we identify the following three challenges related to monitoring the home environment: the cost, the reliability and the issues of privacy.

Cost of monitoring

The energy monitoring process is in itself expensive and the electricity and financial cost can easily erase an important part of the expected benefits. An experiment by Lachut and colleagues showed that home electricity monitoring can represent up to 44% of an off-grid house consumption (Lachut, Choudhury, & Banerjee, 2012). An off-grid house is not connected to the electricity grid and therefore does not have access to a lot of electricity relying purely on solar electricity generation. It is important to mention this figure relies on an off-grid house in California consuming only 2.5kWh a day. We will see in Chapter 5 that it is four times less than the lowest consumption of our participating households. This additional electricity consumption from sensors, electrical meters and other tools used to monitor the environment, can thus be problematic for such off-grid houses although typical consumption from monitoring on normal grid-connected homes usually represents an insignificant fraction. Different sensing solutions are proposed to reduce the number of sensors in order to reduce the electricity consumption and the installation cost. TinyEARS and Viridiscopes are projects that combined electrical meters with cheap sensors such as audio or light sensors (Taysi, Guvensan, & Melodia, 2010; Kim, Schmid, Charbiwala, & Srivastava, 2009). These solutions reduce the cost and the electricity consumption but are still intrusive: they require installing sensors in different places in the home. They often come with a wireless on-off switch allowing householders to remotely control the appliances connected to it. These switches have gained in popularity and are the main ingredients used when implementing ‘smart’ homes.

Minimising the energy and financial cost of monitoring is essential for a viable Demand-Shifting process. On the one hand the direct objective is not to reduce the electricity consumption but it should not increase it either. On the other hand, the financial cost must remain as low as possible: while the impact of Demand-Shifting is important at the grid scale, the benefits for a single house are limited. Non-Intrusive Load

Monitoring (NILM) is a recent technique that reduces the intrusiveness and the cost of sensing while providing per-appliance electricity consumption. This system is composed of only one sensor plugged in the home and follows four main steps: data acquisition, event detection, feature extraction and classification. Patel and colleagues implemented such a system that can be plugged into any power outlet to monitor the whole house by detecting noise signatures of on-off switches. Their system makes it possible to know the consumption of each appliance in real time with an accuracy ranging from 80-90% (Patel, Robertson, Kientz, Reynolds, & Abowd, 2007). While reducing the intrusiveness and the cost of monitoring, NILM solutions do not provide controls on each appliance.

Emerging privacy issues

These new monitoring technologies bring new issues of privacy: anyone who accesses the overall electricity consumption of a household is able to observe most of the householder's activities. Smart meters are new electricity meters that enable real-time interaction between the electricity provider and each household as part of the smart grid development. The provider sends the current electricity tariff and households send the current overall electricity consumption. On one hand, this communication supports better electricity grid management. On the other hand, it allows to identify most of the activities of a household by simply looking at the smart meter's data. In fact, 68% of records can be reidentified from the overall electricity consumption with simple means (Buchmann, Böhm, Burghardt, & Kessler, 2012). A malicious person could be interested in this information, for example to know when the home is unoccupied in order to burgle it. Electricity companies can be interested in per-appliance consumption and consumption profiles to improve their peak-load prediction algorithm.

Several solutions are proposed by Molina-Markham to address this new issue: (i) neighbourhood gateways which mix data with other households data before transmit them without identification risk; (ii) a zero-knowledge protocol which provides a support allowing a 'prover' with a secret (householder) to be challenged by a verifier (electricity provider) without giving away the secret; or (iii) adding noise to load signatures using rechargeable batteries (Molina-Markham, Shenoy, Fu, Cecchet, & Irwin, 2010). These emerging privacy concerns are out of the scope of this research. However, they have to be clearly considered when we collect householder's data, even for the purpose of a study. The right monitoring for Demand-Shifting balances risks and costs with the benefits.

While sensing the actual context is a first step in the Demand-Shifting mechanism, it does not provide much opportunity to intervene and shift the demand: at real time it is only possible to postpone the demand. In the next section we present the mechanism to look ahead and anticipate.

2.4.2 PREDICTING: WHAT IS GOING TO HAPPEN?

Looking ahead relies on the prediction of what is going to happen, generated by the system itself or accessed from external sources. Having a picture – as precise and accurate as the system can make – of upcoming events allows it to anticipate. This is key in the Demand-Shifting mechanism as it provides the opportunity to prepare the system for a future event. In contrast with the real-time information offering only the option of postponing activities, predictions allow the system to act in advance and trigger or schedule events earlier than they were supposed to happen. Thus, it is important to predict when the solar electricity will be available and when electricity loads will be required in order to determine the right moment to shift electricity demand.

Prediction algorithms go beyond the scope of this research project. However, the entire project relies on these predictions. It requires us to understand the main techniques of prediction and the existing methods in order to implement them.

Prediction of Domestic Solar Electricity Generation

It is important to know when the solar electricity generation will be available. Sharma and colleagues determined that the weather forecast metrics related to solar electricity generation are temperature, dew point, wind speed, sky cover, precipitation and humidity (Sharma, Sharma, Irwin, & Shenoy, 2011). Because this combination of parameters has to be specific for each household, they propose a machine learning algorithm to learn the local conditions and produce predictions. A different approach was used in a network of 80 domestic solar PV systems distributed over 50 km² (Lonij, et al., 2012). The power generation of these systems was sent to a central server which combined these data with the direction and the velocity of clouds. From this information, each solar PV system received a one-hour prediction based on neighbouring solar PV systems and cloud variables.

Prediction algorithms for solar electricity generation can be found in other domain. For example, Noh and colleagues focused on wireless sensor networks which often rely solely on solar electricity and must manage their power consumption carefully. They combined historical data about harvested electricity and current conditions such as cloud coverage and temporary problems (e.g. obstacles) as a method for prediction. In the

domain of data centre infrastructure, which requires large amount of electricity, a similar approach was used by Goiri who combined historical data with weather forecast (Goiri, et al., 2011). Their objective was maximising the use of electricity produced through wind turbines.

Prediction of Domestic Electricity Consumption

It is difficult to predict local overall electricity consumption and per-appliance electricity consumption. As the starting point for electricity supply planning, many different methods and algorithms have been designed for electricity load forecasting (Feinberg & Genethliou, 2005). However, all these methods are designed for a large scale forecast, rather than single house or several houses. With a smaller number of houses, the prediction of electricity consumption is less predictable. A large appliance that is turned on or off can have a significant impact on the overall consumption and it is difficult to predict. The resident occupancy prediction can provide important information to improve electricity consumption prediction.

Occupancy prediction can also be used to adjust supply to the need. For example, Scott and colleagues proposed a pre-heat and early-off system based on resident's occupancy (Scott, et al., 2011). Thanks to occupancy GPS-based prediction, the system is able to pre-heat the house to provide requested temperature when the residents arrive and stop the heating system when they leave the house. Three benefits are achieved: comfort improvement with the right temperature, no loss of time to define a heating schedule and energy consumption reduction thanks to the reduction of periods of heating with no one at home.

Prediction of appliance usage

The prediction of domestic consumption and generation provides an estimation of the size of the energy gap for the coming hours. In combination with external predictions such as electricity tariffs and grid carbon intensity, the system can determine when it should be the appropriate time to reduce or increase the household consumption. The system, though, needs to estimate which appliances will be used over the coming hours to evaluate what could be shifted.

Lachut and colleagues challenged the question '*how predictable is home energy usage?*' (Lachut, Banerjee, & Rollins, 2014), comparing the performance of four representative prediction algorithm – covering k-nearest, Bayesian, Support Vector Machine (SVM) and time series (autoregressive moving average (ARMA)) – against a 'simple' prediction that use the value monitored in the previous time-slot as prediction of the next time-slot. They highlight that the simple statistical prediction has a comparable accuracy to sophisticated algorithms and

that additional features such as time of the day and day of the week do not improve the accuracy. It is a strong argument against embedding complex algorithms – and thus energy, memory and time – into domestic energy management devices. The authors raise the importance of taking prediction accuracy into account when designing home energy system, highlighting that predictions over a longer horizon can drop to 50% of accuracy. Finally, they recommend that any energy saving recommendation system should be fine-tuned to the householder because there is high variation of accuracy of prediction between appliances and between households. It is worth mentioning that the definition of what the authors call ‘Prediction Accuracy’ is not precisely defined.

Basu and colleagues propose a generic model to provide an appliance usage prediction (Basu, Hawarah, Arghira, Joumaa, & Ploix, 2013). Based on the past consumption and periodic features including the hour of the day, the day of the week, the month and the season they provide a binary prediction: whether or not the appliance will be used on a given time-slot. The objective of Truong and colleagues is also to predict appliance usage (Truong, McInerney, Tran-Thanh, Costanza, & Ramchurn, 2013). However, they consider the dependency between appliances, between days and within days. Building on the prediction of ‘Going out’ (Tominaga, Shimosaka, Fukui, & Sato, 2012), they propose the GM-PMA algorithm (for Graphical Model for Prediction of Multi-Appliance usage) to model and predict all appliance usages at once rather than predicting each individual, thus reflecting the daily routines in the household. This model generates from previous observations a list of types of day such as ‘laundry day’, ‘working day’, ‘family day’ and so on. A type of day represents for each appliance and each period of time the likelihood that this appliance will be running. The model uses these typical days to infer the type of day to predict. The authors assume a cyclic weekly pattern in the daily routine, thus include in the prediction process the day of the week as a known value. Evaluating their prediction on both synthetic and real world datasets, they show that their algorithm performs better than the state of the art algorithms.

In this section we briefly presented prediction algorithms for local solar electricity generation, overall electricity consumption and appliances usage. The combination of these predictions shapes the view of the system on future situations. In contrast with the data gathered at real time, the predictions provide more flexibility to take action in advance. For instance, the Demand-Shifting mechanism can anticipate an overconsumption and look for electric loads that could be run earlier and thus shave the peak of consumption.

The system, though, still does not know what would be the best to do. The next section presents the potential optimisation which combines both actual and predicted data with objectives to determine the best situation that could be reached.

2.4.3 OPTIMISING: WHAT WOULD BE THE BEST?

From the actual and predicted data, it is interesting to determine what would be the best way to organise appliance usage depending on objectives such as maximising the use of local generation, maximising the comfort of householders and so on. Such information can be used to tune the system or provide suggestions to the user in order to improve the system. In this section we present existing taxonomies of appliances highlighting shifting opportunities. Then we detail approaches to the scheduling problem.

Appliance taxonomies

In order to shift appliances, it is important to determine what can be shifted as well as the various operational and technical constraints. Several research projects have worked out taxonomies of appliances in this objective. Allering and colleagues distinguished **controllable** and **observable** devices (Allering & Schmeck, 2011). In the **observable** category we can find **predictable services** (e.g. a stove or hob that is always used before meal times) and **unpredictable services** (e.g. lighting which is dependent on the weather and personal preferences). Controllable appliances are observable. In addition, they have the ability to receive external control. We can find **permanent services** that run continuously (such as a deep-freezer) and **timed services** (e.g. a dishwasher) that are available for a given period after a user interaction. In Portugal, Soares and colleagues proposed a classification of controllable appliance's loads based on an analysis of the Portuguese domestic electricity consumption and the consumption pattern of appliances. They distinguish between non-controllable loads (controlling them may cause a user discomfort), **shiftable loads** that can be postponed or anticipated according to end-users' preferences, **interruptible loads** that can be stopped for a short period of time and **re-parameterizable loads** that can be re-set (Soares, Gomes, & Antunes, 2012). Similarly, Zhu and colleagues presented classification based on three categories: **non shiftable** (e.g. watching live television), **time-shiftable** (e.g. a washing machine) and **power-shiftable** (e.g. a water heater, or phone charger) (Zhu, Tang, Lambbotharan, Chin, & Fan, 2012).

These taxonomies present multiple categories and small variations, highlighting that each project's authors defined their categories that suit their project. Most of these taxonomies rely on limited user study if any.

There is no clear distinction between ‘technically unfeasible’ (e.g. reducing the power of the washing machine), ‘no sense’ (e.g. starting the washing machine without clothes in the drum) and ‘unwanted by the user’ (e.g. running the washing machine after 10PM). Furthermore, there is no flexibility for an appliance to be shiftable or not depending on the time of the day, or depending on the households. In this section we thus shed light on the various opportunities and constraints for each appliance, highlighting the need for a better taxonomy. In Chapter 6 we present a taxonomy of appliances as part of our framework.

Scheduling

Scheduling is the process of sequencing events to optimise one or several resources. In the context of domestic solar electricity generation, electricity load scheduling can help to balance electricity generation and electricity consumption. In this section we highlight the approaches to domestic scheduling with different focuses on the objectives and appliance types.

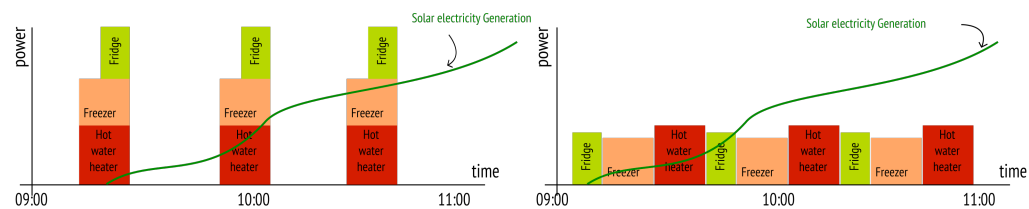


Figure 2-13 Flattening the demand of appliances running in the background. a: appliance loads’ overlap which requires importing from the electricity grid, b: the same appliance loads scheduled in order to reduce peaks of electricity consumption.

A first approach to appliance scheduling is focusing on ‘background’ loads – loads of appliances running behind the scene which do not require any intervention from the resident such as air-conditioners (A/Cs), refrigerators, freezers, dehumidifiers, and heaters in contrast with interactive loads like microwave ovens or televisions. The relevant property of these appliances is their need to turn on and off every so often without user intervention. For instance, the refrigerator turns on every time its internal temperature is too high. In the case where these appliances turn on together, they create electricity consumption peaks (see **Figure 2-13**). These loads can be shifted backward or forward in time to better sequence them and reduce the overall peak as long as it does not violate appliance constraints (e.g. temperature threshold). In the scheduling literature, a *slack* is defined as the extent to which the electricity consumption of a load can be advanced, deferred, raised or lowered. SmartCap is a project aimed at flattening these consumption peaks from background appliances (Barker, Mishra, Irwin, Shenoy, & Albrecht, 2012). They propose a Least Slack First (LSF) policy. In more detail, the algorithm will give priority to appliances which are closer to their shifting limit (e.g. the refrigerator about to reach its temperature limit). Householders do not control background appliances but

influence their consumption pattern. For instance, a householder opening the refrigerator will impact on the cycle of this refrigerator which will require the next cooling cycle to run earlier. While the interactive appliances are not controlled, loads of background appliances can still be shaped around them instead of running at the same time.

Another approach to appliance scheduling is focusing on interactive loads. In this case the scheduling problem relies on one or a set of objective functions and a set of constraints. The constraints can be technical (e.g. a device cannot run two loads at the same time), operational (e.g. the washing machine loads needs to be done before starting the tumble-dryer) or users (e.g. the dishwasher load need to be done by 6 PM). Bapat and colleagues model the scheduling of appliances with an Integer Linear Program (ILP) to minimise the electricity and inconvenience cost (Bapat, et al., 2011). An ILP objective function is defined as a single linear equation that combines all the objectives. The inconvenient cost relies on a ‘preferred usage profile’ extracted from the historical data – assuming passed usage as preferred usage – by computing the time and power distances. The ILP outcomes provide a ranking of the best solutions.

Soares and colleagues relied on a genetic algorithm to schedule domestic appliance loads. In contrast with a single objective or multi-objective presented as one unique objective function, genetic algorithms can solve multi-objective problems directly. The authors define two objectives: the electricity cost and the user’s dissatisfaction. Genetic algorithms follow the principle of natural selection.

In this section we looked the existing taxonomy of appliances to observe the shifting potential of appliances. Then we detail approaches and algorithms to schedule domestic appliances. We introduced the main concepts and algorithm for scheduling. We also highlighted the impact of the users, either for background or interactive appliance scheduling, that we call ‘resident-computer interaction’ in the next section.

2.4.4 RESIDENT-COMPUTER INTERACTION

The home is a specific context. In this section we present the reasons and challenges of this environment driven by ‘residents’. As highlighted by Crabtree and Rodden, there is a fundamental difference between the home and the workplace: the home is not driven by productivity. Concepts of production and efficiency in domestic life cannot be adequately described in formal terms of capital production (Crabtree & Rodden, Domestic routines and design for the home, 2004). The home is not characterised by a common orientation

towards a shared work objective but is characterised by multiple objectives depending on the context and the residents.

‘Routines mean that people can get out the door, feed themselves, put the children to bed, and so on, without eternally having to take pause and invent sequences of action anew or open up their every facet for inspection or challenge or to constantly have to account for what they are doing with explanations or rationales.’ (Crabtree & Rodden, Domestic routines and design for the home, 2004)

Domestic routines, described by Crabtree and Rodden as automatisms, allow residents to complete typical actions without thinking about it. Smart home technologies must follow these informal patterns which can be broken at any time. A study showed that what people consider as ‘Smart’ is not especially advanced technology but what fits routines and avoids unnecessary work. Further, it is not smart if they can do it better (Mennicken & Huang, 2012). Building Management Systems (BMS) have a tendency to focus on automation while severely curtailing the involvement of inhabitants in building control. Yet several studies have pointed out that buildings designed to be carbon neutral are found not to be so in practice, and much of this difference between the design intention and the actual performance is due to the behaviour of occupants and the complexity of the interface to energy management systems. Half of all energy consumption is under the control of residents (Schipper, 1989). Usability studies of home thermostats found that homes with programmable thermostats consumed more energy than those relying on manual thermostats (Meier, Aragon, Peffer, Perry, & Pritoni, 2011): occupants found thermostats baffling to operate and many people were unable to fully exploit even the basic features of modern programmable thermostats. Furthermore, a recent study of the NEST automated thermostat showed that while residents initially were engaged in interacting with the new device, over time they settled into patterns that resulted in missed opportunities for energy savings (Yang, Newman, & Forlizzi, 2014).

Contrary to naive assumptions, inserting more automation, including distributed sensors and algorithms, does not automatically lead to a simpler, more effective or less stressful role for humans (Parasuraman, Sheridan, & Wickens, 2000). Extensive literature in robotics (Pina, Cummings, Crandall, & Penna, 2008) and plant control (Cummings & Thornburg, 2011) (O'Hara, Higgins, & Brown, 2008) has pointed out the brittleness of human-automation collaboration and identified fundamental models of human-automation collaboration, such as ‘human on the loop’ vs ‘human in the loop’. As everyday environments and buildings start to incorporate aspects of intelligent systems, it is important to investigate how non-technical users interact with intelligent systems.

Davidoff and colleagues conducted a field study with 12 dual-income families, combining 3-hour contextual interviews with cultural probes and a diary study (Davidoff, Lee, Yiu, Zimmerman, & Dey, 2006). They illustrated the complex relationship between the resident and a smart home system through a list of seven principles:

1. *'Allow for the organic evolution of routines and plans'.*
2. *'Easily construct new behaviours and modify existing behaviours'.*
3. *'Understand periodic changes, exceptions and improvisation'.*
4. *'Design for breakdowns'.*
5. *'Account for multiple overlapping and occasionally conflicting goals'.*
6. *'The home is more than a location'.*
7. *'Participate in the construction of the family identity'.*

This list of requirements highlights the main challenges of resident-computer interaction. More than control of their devices, families desire more control of their lives. This requires more flexibility and appropriately reflecting on the complex nature of observed human interaction. In other words, it is important to understand routines in order to participate in the construction of the family identity without challenging it.

This section highlighted the important place of the householder as user in the home and the way daily routines make the resident-computer interaction a challenging exercise. The user is at the core of the investigation and evaluation methods throughout this research project.

2.4.5 SUMMARY: INGREDIENTS WITHOUT THE RECIPE

Through this section we presented the four ingredients of the Demand-Shifting mechanism. Knowing what is actually happening in the environment is the first step to determine what is going right or wrong. Does the system consume more than it generates? Which devices are consuming? We detailed technology enablers to monitor the environment, noting the concerns about privacy and the importance of monitoring cost. Then we move on the prediction of what is supposed to happen that allows users to anticipate a situation and prepare the system – depending on available controls – to face a situation. For instance, a surplus of solar generation in the morning or a washing machine load in the evening are two events which need to be known in advance to provide the system the possibility to improve the coming situation. Knowing how the best situation should look like either in real time or in the future is also important to search for potential improvements. The more accurate actual and expected information the system has, the most realistic the ideal situation will be. For

instance, an accurate prediction of solar generation and washing machine loads allows the system to determine the best time to do the laundry to get the most power from the sun.

While technical challenges remain, we highlighted that technology enablers exist for monitoring, predicting, optimising and interacting with the users. However, the combination of these ingredients in a realistic setting remains a key challenge. It requires complying with heterogeneous and resource constraints domestic environment, interacting with various householders and dealing with unpredictable events or inaccurate prediction.

2.5 CHAPTER SUMMARY: TOWARDS A SUPPORTIVE DEMAND-SHIFTING MECHANISM

In this chapter we defined and motivated the Demand-Shifting mechanism as an opportunity and a solution to reduce the energy gap at the intersection of the energy, human-computer interaction and software engineering domains.

First, we presented the necessary energy background from the grid to the house, highlighting key issues: (i) the domestic energy system is complex, (ii) micro-generation such as solar PV are most suitable for domestic settings but (iii) their uncontrollable generation are out of sync with domestic consumption. Relying on a detailed overview of the grid, we summarised the technical optimisation of the domestic electricity with micro-generation in the UK as **minimising the import from and the export to the grid**.

Then, we motivated the Demand-Shifting based on early evidence in the context of domestic micro-generation: in this context, householders tend to naturally shift their consumption to get the best out of their local electricity generation. However, there is no clear understanding of this emerging practice yet. Hence, this thesis looks at:

RQ1. How do Demand-Shifting practices take place in the context of domestic solar generation?

Then, we reviewed the existing approaches to Demand-Shifting from fully autonomous home automation solutions to fully human controlled solutions. We highlighted opportunities of in-between solutions supporting householders' everyday life routines. Although, at this stage the form and requirements of such a supportive system remains, leading to the second research question:

RQ2. What are the requirements for the interaction between system and householders when the aim is to support Demand-Shifting practices?

There is a major fracture between the three approaches we reviewed, especially between Demand-Response and Eco-feedback: they rely on the work of different research communities, respectively from software engineering and energy, as well as Human Computer Interaction and Ubiquitous Computing. This thesis fills the gap of Demand-Shifting at the intersection of these communities.

Finally, we detailed the main ingredients of the Demand-Shifting mechanism including sensing the environment, looking ahead to predict future situations, searching for potential optimisations and interacting with the householders. However, a major challenge remains on combining these ingredients:

RQ3. How can we design a realistic and interactive digital system to support domestic Demand-Shifting?

Thus, in this thesis we aim to formalise the Demand-Shifting mechanism at the intersection of the research communities through:

- A qualitative picture – extending the understanding of householders’ daily routines in the context of domestic solar electricity generation and the relationship between domestic consumption and generation;
- A quantitative picture – weighting empirically the potential of shifting appliances;
- An engineering picture – designing systems that aim to support householders shifting their consumption.

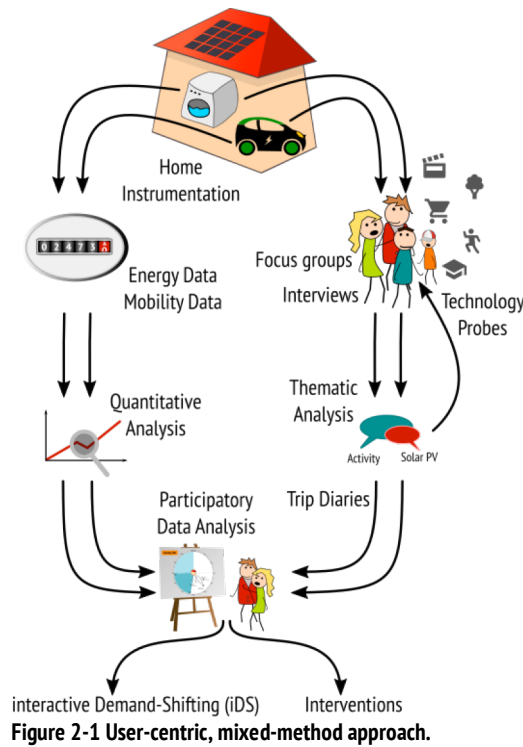
To this end, the next chapter presents the overview of our mixed-method approach.

Research Methodology

A Mixed-Method Approach

‘A new type of thinking is essential if mankind is to survive and move to higher levels’

ALBERT EINSTEIN, NEW YORK TIMES MAGAZINE – JUNE 23, 1946



In perspective of the literature review, this chapter motivates the user-centric mixed-method approach of this project and the way it fills the gap between user interaction and software engineering research. First, we present the epistemology of the research, reflecting on the recent research methodology used for studying technology in the home. Then, we discuss the choice of the appropriate evaluation methods selected to address the research questions. We derive the necessary investigation methods in order to meet the research philosophy and the evaluation requirements. Finally, we draw the map of the data collected throughout the research project, highlighting our collaboration with the energy provider E.ON and discussing the ethics of the research studies.

3.1 A MIXED-METHODOLOGY APPROACH

Figure 2-1 illustrates the overall methodology of the project, following a mixed-method approach centred on the domestic context. On the one hand, our home monitoring provided quantitative data and a numerical view on domestic electricity and mobility. On the other hand, our discussions with householders generated qualitative data and a rich view on domestic routines. In this section we briefly review the existing methods to study technology in the home and the benefits of using a mixed-methodology to achieve our research objective.

3.1.1 STUDYING TECHNOLOGY IN THE HOME

As we highlighted through the context of this research, the relationship between energy and people is becoming more complex. A new challenge is emerging for designers of energy systems, HCI researchers and social scientists who are interested in understanding the interdependence between technology design and human energy practices: what methods do we use to investigate behaviour change, and changes in attitudes and self-image? Observing and understanding behaviour change in a real world context, such as a home or a large organisation, is difficult. The home is a highly contextual environment steered by everyday life, habits and implicit rules.

As a results of the CHI '13 workshop 'Methods for studying technology in the home' in which we participated, Coughlan and colleagues discussed the current issues of studying technology in the home and present an agenda of the future research directions (Coughlan, et al., 2013). They highlight the need for mixed-method and cross disciplinary research, the installation and capture of data via technology, the understanding of human behaviour and the need to create and evaluate designs. One of the main challenges they highlight is to put potential users of future technologies in a setting that help them envisage how a novel technology might fit into their own household context. Another challenge is how to collect information on 'transparent actions' that are of little interest to the participants. For instance, how do we highlight daily routines which drive householders but that are carried out without thinking about it. While long-term ethnographic observation is difficult, techniques to replay or highlight these hidden routines are essential to build a deeper understanding of the context and the decision-making process taking place. Finally, Coughlan and colleagues highlight the active contributions of the participants to the research process. Engaging participants and making them feel they have gained from taking part of the research could be a way of getting deeper insights. This last point connects to the place of the researcher in the home setting in which it is necessary to find the right balance of presence and getting away to avoid biasing the findings.

3.1.2 RESEARCH EPISTEMOLOGY

In perspective of the home context and the nature the research objective, we started our research with the assumption that Demand-Shifting can neither be investigated through a positivism/post-positivism nor a constructivism knowledge claim. While the first aims to reduce the problem to a deterministic one in order to verify a theory, the second relies on the compilation and interpretation of participants' meanings to generate

theories. These two research philosophies have opposite paths to reach the objective, though they both seek for an absolute truth. Instead, our research approach can be better explained as a pragmatic approach, by some referred to as the pragmatism knowledge claim (Creswell, 2003, p. 12), which focuses on the problem with the freedom of selecting the most suitable methods, techniques and procedures of research to address the research questions. Most importantly, as pragmatists we are not looking for an absolute truth but rather a relative one, tied to the time and context of the research. In this context, the truth is what is useful and solve the given problem. This paradigm fits better with studying technology in the home, following evidence that ‘one size does not fit all’ and the necessary personalisation of a solution to the context of each household and each period of time.

The mixed-method approach follows pragmatic knowledge claims with a collection of both quantitative and qualitative data. It appears the most suitable approach for this research, taking the strengths and characteristics of both types of data, collected through a range of methods to strengthen each other’s results, thus providing a better understanding of Demand-Shifting.

3.1.3 FOCUSING ON TWO DOMESTIC ROUTINES: DOING THE LAUNDRY AND ELECTRIC MOBILITY

As we highlighted in the previous section, it is challenging to study technology in the home because of the complexity of the multiple routines and their connections. It is also part of the pragmatism principles to present findings in relation to a particular context. Thus, we chose to zoom into two particular domestic routines: doing the laundry and the electric mobility. **Figure 3-2** presents an overview of the four studies we conducted.

First, we focused on laundry routines and the washing machine in the context of domestic solar generation. The washing machine appears as an obvious candidate for electricity Demand-Shifting. Doing the laundry is a well-established core routine in most households, ingrained into and influenced by other domestic routines. Then, we took experience of our studies focused on the washing machine to look at the Electric Vehicles (EV) and mobility routines in the context of domestic solar generation. EVs are new home electricity consumption that disrupt or create new routines. In contrast with the washing machine, EVs are high consuming appliances. We use this second investigation to echo and refine results observed around the washing machine in order to highlight potential gaps and relations between appliances relevant to the support of Demand-Shifting. We used a similar methodology for both washing machine and electric vehicle studies, involving exploration,

understanding and design of prototypes to support householders. We present the details of these studies in chapters 4 to 7.

The triangulation of qualitative and quantitative analysis is a major aspect of the mixed-method approach. We performed this combination of data in both washing machine and electric vehicle studies through the personal infographics and discussion with householders. In Chapter 5 and 7, we detail the design and implementation of this method we call Participatory Data Analysis (PDA), which combines quantitative and qualitative data to build more comprehensive research outcomes in collaboration with the participants.

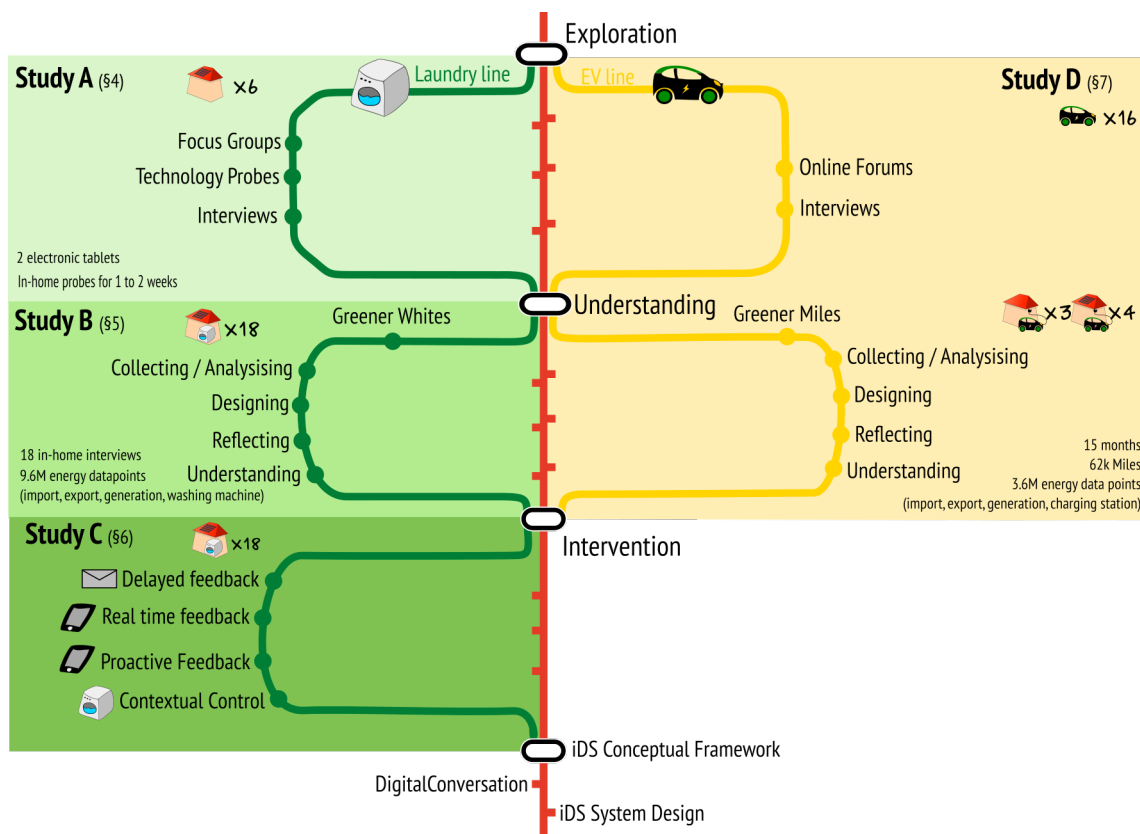


Figure 3-2 Overview of the studies.

Going back to **Figure 2-1** we summarise our research methodology as a mixed-method approach relying on two contextual investigations – the laundry and the electric mobility routines – which involve exploration, understanding and intervention in the context of local solar electricity generation. We give an important place to the householders who take part in the process from the exploration to the analysis.

3.2 EVALUATION METHODS

A mixed-method approach requires to combine multiple evaluations in order to meet the requirements of each method. In this section we build an overview of the evaluations we used, discussing choices and motivations in relation to the research questions.

3.2.1 THEMATIC ANALYSIS

Through RQ1 and RQ2 we want to understand the process of a domestic routine to extract needs and constraints. Thus, it requires in-depth discussions with householders to extract this information. We used the thematic analysis to explore these discussions and organise the data in ‘themes’, capturing the important elements in relation to the research questions (Braun & Clarke, 2006, p. 82). This method provides flexible guidelines to gain insights from exploratory data. In particular, we followed the six phases of a thematic data analysis described by Braun and Clarke (Braun & Clarke, 2006) as described below. In terms of tool support, for the study on laundry routines, we used Latex with the package ULQDA (Griffin & Richardson, 2010) – which is possibly now considered an outdated way of performing such a thematic analysis – while for the mobility study, we implemented the analysis through NVivo. For both studies:

Phase 1. We fully transcribed the video or audio records made for each interview. Video recording had been made alongside the audio recording to ensure at least one usable record existed, but no video analysis was actually performed. However, it has been a useful material with some of the interviews, as we could see what interviewees were pointing at when they were talking.

Phase 2. We went through the transcription and performed an initial coding of the data. These codes were both categories that we were expecting such as 'washing machine', 'other appliances', 'routine'..., but also and mostly any words that were standing out as we were reading each extract.

Phase 3. The third phase is called 'searching for themes' and this is an iterative process. Both Latex ULQDA and NVivo produce a list of all the codes that have been inserted in the data which makes it easier to look at all of themes at the same time. Rereading these codes after each iteration through all the data, some of them had become meaningless and were removed. This phase requires scanning the data, again and again, refining the codes by splitting and merging them until themes begin to appear more clearly.

Phase 4. When we felt there was no more significant improvement after going through the data, we initiated the next phase (4) which is about ‘reviewing the themes’. We reviewed the themes, reading the extracts of each group (each theme) to see if the content was homogeneous and made some adjustment.

Phase 5. Defining and naming the themes. In this phase we started drafting a report of the study and build the outline using the themes and subthemes as headers.

Phase 6. Reviewing each theme, we further worked on the body of each section from the outlines to ‘produce the report’. Having produced the report, it then became easier to read a subgroup of extract, write about a theme and also to pick up one or a couple of extracts as examples in the write-up of papers and this thesis.

The outcome of this work takes the form of a discussion for each study and an overall discussion, highlighting similarities and contrasts. Without generalizing, we used these discussions to formalise a conceptual framework of interactive Demand-Shifting (iDS) in perspective of the literature.

3.2.2 EXPLORATORY DATA ANALYSIS

While in-depth discussions with householders provide a rich picture of routines and practices, they rely on what participants are willing to tell us or what comes into their mind through the discussion. To strengthen or nuance these outcomes, it requires to look at energy behaviours through electricity monitoring. Analysing electricity generation and consumption provided us with an objective view on energy practices and the potential benefits of Demand-Shifting for each participating household. In combination with the qualitative analysis, we provide high contextual insights in the context of domestic micro-generation. Specifically, quantitative analyses of this research project explore and compare the timings and magnitudes of loads in the home energy ecosystem.

To this end, we performed an Exploratory Data Analysis, or EDA as presented by John Tukey (Tukey, 1977). In contrast with Classical Data Analysis (CDA), we were not bound to an initial model or assumption. This freed our exploration from using measures of significance which our limited sample of participants and time of collection could not comply with. Instead, our quantitative analyses are rather descriptive, suggestive and insightful. We build up tech pictures of electricity consumption and production from a variety of data, both qualitative and quantitative, where taken together these provided a view of electricity in the home that is both about magnitude and timelines but also about human relationships around this usage. Because data belonged to individual households that we were familiar with (through the interviews), we used these insights to explore the data. Being able to provide such deep insights is a strength of our work. We present two detailed examples

in pages 87 and 137. The outcomes of this evaluation come to strengthen and nuance our discussions and highlight the potential benefits of the Demand-Shifting mechanism.

3.3 INVESTIGATION METHODS

We selected the evaluation methods to meet the requirements of the mixed-method approach and to address the research questions. In this section we present the investigation methods we used to collect the adequate qualitative and quantitative data.

3.3.1 IN-THE-WILD RESEARCH

The overarching objective of this thesis is about getting a better understanding of the domestic Demand-Shifting practices and design tools to support these practices. ‘The Turn to the wild’ (Crabtree, et al., 2013; Rogers, 2012) highlights a need to adapt the research methodology to the rapidly growing development of pervasive technology is intricate within our daily routines. The lack of boundaries between the technology and the context requires to investigate in situ the way it is used and its impact on people. In contrast with ethnography, there is no initial step in which the researcher observes the practices in its original context. Through in-the-wild interventions the researcher observe how people react and make use of a technology, a design or a concept. In-the-wild research also differs from action research, as the goal is not to fit in with existing practices but rather understand these practices and seek to support, change or disrupt them. In-the-wild research helps revealing unconscious decision-making taking place in everyday life and developing supportive technologies.

3.3.2 RESEARCH THROUGH DESIGN

In combination with a user-centric methodology, we used design activities throughout the research project, making it part of the research process. For example, we designed a number of probes, using the Technology Probes approach in order to explore a variety of issues (Chapter 4), and we also designed infographics in order to explore data issues together with participants (Chapter 5 and Chapter 7). To further build up our understanding and insights, we designed and deployed functional in-home prototypes which allowed us to actually observe participants interacting with these prototypes in their home-setting (Chapter 6).

Frayling coined the term ‘Research through Design’ (RtD) in 1993 (Frayling, 1993) among three ideas of research *for*, *into* and *through* design. Used in interaction design, RtD aims at generating knowledge rather than

a product, stressing design artefacts ‘as outcomes that can transform the world from its current state to a preferred state’ (Zimmerman, Forlizzi, & Evenson, 2007). The main challenge of RtD is its evaluation. Zimmerman and colleagues (Zimmerman, Forlizzi, & Evenson, 2007) present four criteria for evaluating interaction design research within HCI:

- Process – It is recognised that reproducibility cannot be expected to generate the same results. However, the research quality is assessed based on the documentation describing the methodology and the research procedure used for the study.
- Invention – The design has to be presented as filling a research gap, fitting clearly in the state of the art to provide ‘significant advancement’.
- Relevance – Providing strong motivations for of the design is of first importance, by showing that the design lead to or support a preferred state, and why it is so.
- Extensibility – Can we leverage the presented outcomes?

Throughout this research we engaged with this approach to research aiming to comply with these criteria, giving a particular attention into describing the design process, sitting the proposed design into the state of the art, motivating the design and drawing an agenda for future research.

3.4 DATA COLLECTION

Following the mixed-method approach presented above, we collected qualitative and quantitative data of multiple types and from a wide range of sources. In this section we introduce our collaboration with E.ON which provided us with a rich set of data. Then, we detail the technical settings which enabled most of the data collection throughout the project. Finally, we present the type and purpose of the data we collected.

3.4.1 INDUSTRIAL COLLABORATION: E.ON AND THE THINKING ENERGY PROJECT

We conducted this project in collaboration with E.ON, an international energy provider running the *Thinking Energy Project*²³, a European-wide trial begun in early 2012 with 75 participating households around Milton Keynes (UK), close to the Open University. *Thinking Energy* aims to understand how households can manage domestic energy use through technologies ranging from smart meters and smart plugs to smart washing machines and EVs. The keen interest of E.ON in this project highlights the benefits an energy provider can get out of a better understanding of their customers. The Thinking Energy project represents an investment of £1.5m per year and approximatively 3.5k Man-Days over 4 years.

²³ Thinking Energy: <http://pressreleases.eon-uk.com/blogs/eonukpressreleases/archive/2012/09/19/1861.aspx>

The original recruitment of households for the larger E.ON trial was conducted by E.ON through different steps: Emails were sent to Milton Keynes Council (MKC) staff and letters posted door-to-door to targeted areas (6000). Interested participants were required to sign up to the National Energy Foundation website and invited to a local event (118). Finally, home surveys were then conducted and 75 participants were selected. These participating households were from different energy providers, not necessarily E.ON customers, located around Milton Keynes, a medium-sized UK suburban city. Some of the participating households already had solar panels installed before or installed them during the trial, and most have a keen awareness of energy issues and energy bills.

In 2013, after about a year of general trial across all participants, E.ON divided the initial trial in four groups of participants with additional deployment to focus on different energy efficiency topics. Each participating household filled a wish list to prioritise which group they would prefer to be in, after which E.ON allocated each household to one of the following four groups:

- Greener Whites – Deployment of a connected washing machine;
- Greener Miles – Deployment of an EV;
- Greener Heating – Deployment of a central thermostat and thermostatic radiator valves (TRV) on each radiator for a fine grain control of the temperature in each room;
- Greener Lighting – Deployment of efficient and connected light bubble.

Although E.ON had identified that these were the four areas they wanted to investigate, there was no precise research plan on how to approach this. They were keen to collaborate with universities, and we contributed to setting of the overall direction for the research in the areas of Greener Whites and Greener Miles. In particular, we worked in close collaboration with E.ON and the ‘Greener Whites’ group in studies B and C (Chapter 5 and 6) and, with the ‘Greener Miles’ group in study D (Chapter 8). We were able to conduct interviews with the participating householders, access their data and conduct interventions.

Thanks to this collaboration, we attended focus groups and interviews, organised by a company on behalf of E.ON, which aimed at understanding energy use at home and finding ways to reduce energy consumption. These focus group and interview activities allow participants of the E.ON trial to exchange their views about their own electricity generation and electricity consumption. Participants are invited to give feedback on some of the technologies that E.ON were exploring, such as a web interface to consumption of electricity, smart plugs and other technologies specific to each group. Additionally, they participated in activities that allowed

The infrastructure (**Figure 3-3**) deployed in each participating household allowed the monitoring and the control of appliances in the house via the following elements:

- Three optical meters to measure the imported energy from the grid (the typical fiscal meter), the generated energy from the solar panels and the exported energy to the grid (grey dots in **Figure 3-3**). An additional meter monitored the gas consumption. The meters recorded data every 3 minutes.
- About ten smart plugs which monitor the individual electricity consumption of appliances (blue circles on **Figure 3-3**). A smart plug sits between a power socket and an appliance power plug, with the ability to monitor the power consumption and to switch on and off the power via Z-Wave. Participants were free to use the smart plugs wherever they wanted in the house. They could change both the location and their associated label in the system.

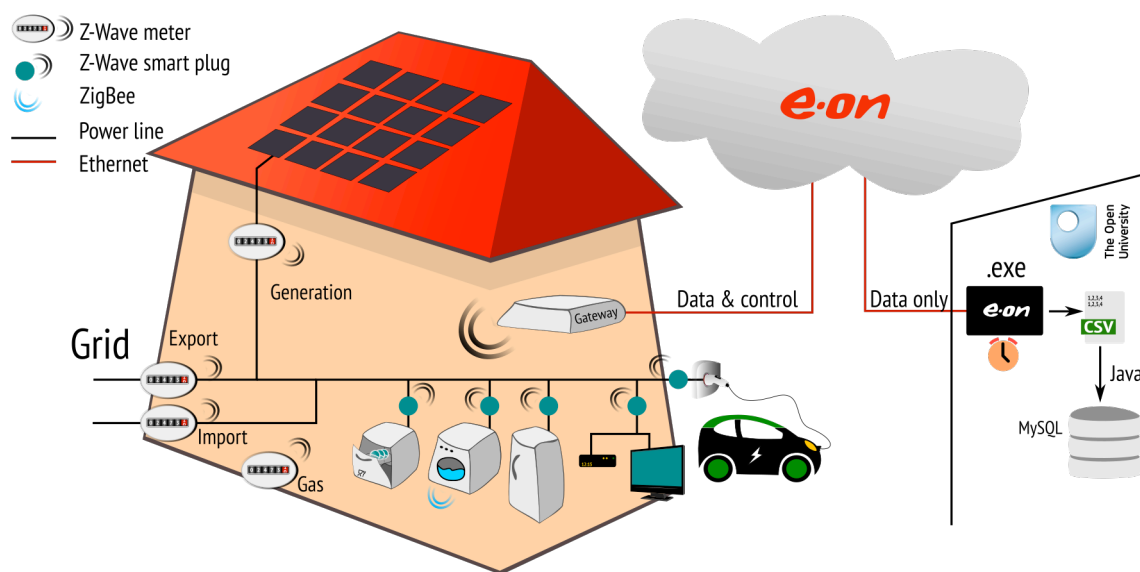


Figure 3-3 E.ON /The Open University initial technical setting. On the left, a typical setting of participating household with a Z-Wave gateway collecting data from smart meters and smart plugs; in the middle, the E.ON server receiving the data and controlling smart plugs; on the right, our data extractor requesting data from E.ON on a regular basis.

- A GreenWave gateway that receives energy data from the meters and smart plugs via Z-Wave and forwards this to a remote server as a typical router.

In addition,

- The ‘Greener Whites’ group received a connected washing machine that can be monitored (programme cycle, pattern of load, etc.) and controlled (start, pause, delay, etc.) via ZigBee.
- The ‘Greener Miles’ participating households received an EV.

Householders were able to access precise consumption data and control their appliances (on and off) from their mobile phone (or tablet) or through a web application. An In-Home Display (IDH) was also provided but because of poor design most participants had stopped using this.

We were given full access to the data of participants that we worked with. However, we were not able to control appliances, as in switching them on or off. E.ON provided us with an executable ‘black box’ that we regularly run on our server at the Open University. This process collects the data from the E.ON server and generates a CSV file that we were then able to parse and store in a MySQL database. On the E.ON server, the granularity of the data is reduced automatically as the data points are getting older, reaching a minimum of one data point per hour after several weeks.

3.4.3 QUALITATIVE DATA

Focus groups and Online forums

We used focus groups and online forums to gather initial insights. The focus groups, organised by E.ON, helped us reflect on the home energy ideas being explored in the trial and gave us insights into the different motivations people expressed, their different family set-ups and how they experimented with range of technologies that E.ON had asked them to use in their home. As observers, we gained a broad overview of the home energy context. As our own work progressed, we were also able to formulate specific questions pertaining to our study that were then explored in the focus groups. In particular, we dedicated a part of a focus group to discussing the prototypes we deployed in participants’ homes.

In the EV study, we explored the posts of two online EV forums which brought to our attention the main topics of discussion in the domain. These forums – namely SpeakEV.com and leafTalk.co.uk – have been valuable to accelerate our immersion into the rapidly growing EV domain.

Interviews

The core of this research focuses on the users and aims to get a deep understanding of the context, the routines and the challenges the users face and the potential support that digital tools could provide. This motivated the collection of qualitative data through semi-structured interviews. At each stage of the research project, we conducted individual interviews with members of each participating household. Most of these interviews took place at the householder’s place and at the most convenient day and time for the householders (including evenings and weekends) to maximise the contextual immersion of the interviews. This approach allowed

participants to take us on tours through their home, where appropriate, to show us devices, settings or replaying routines in situ.

Emails and technical home visits

Occasionally participants would contact us by email to share valuable and spontaneous insights. At various points we also conducted home visits to help fix a technical problem or to install a new piece of technology. Such visits also formed a valuable source of information.

Trip diaries

To enrich our dataset, we asked participants to fill a trip diary over several weeks (p.140). These records contained the details of each trip: departure and destination location as well as time, purpose of the trip and number of people in the car, along with comments from the participants.

3.4.4 QUANTITATIVE DATA

Smart meters and Smart plugs records

Throughout the project, our main quantitative data inputs relied on the E.ON infrastructure presented in Section 3.4.2. It provided instant power data points from the import, export and generation smart meter, allowing us to compute fine-grain electricity consumption and balance – as formalised in Chapter 2 p.14 – for each of our participating households. It also provided instant power data points from multiple appliances via smart plugs. We focused on the electricity consumption of the washing machine and the home EV charging station.

EV mobility: Carwings telematics

We collected data relating to EV trips and charging events through the Carwings telematics, a standard online facility for on-demand traffic information in Nissan Leaf. Each trip record contains the day of a trip with its duration and energy consumption. Charging records contain coarse-grain details on time and energy progression events including their charging mode. We explore this source of data in Section 7.2.1 to enrich our insights of EV routines.

3.5 ETHICS

For both studies we wrote an ethics proforma document which was reviewed and approved by the Open University ethics committee (References HREC/2013/1203/Bourgeois/2 and HREC/2014/1203/Bourgeois/3). These documents include the description of the motivations, the research protocol and a risk assessment.

Enrolment

In both studies, we gave participants an information sheet presenting the objectives of the study and their role as participants in the study. Those agreeing to participate signed a consent form. They were informed that they were allowed to withdraw at any time and they were able to request that their data be deleted at any time during or after the study.

Recompense

The participants did not receive recompense from the Open University. However, as part of the Thinking Energy trial, E.ON gave participants a small monetary compensation for attending interviews and focus group meetings. In addition, E.ON provided them with equipment either for free (e.g. smart plugs, smart meter) or for a much-reduced rate (e.g. washing machines and EVs).

Risks

In both studies, there were no increased risks that participants would come to any harm, as they were using a fully tested washing machine in their normal home setting and a commercial EV.

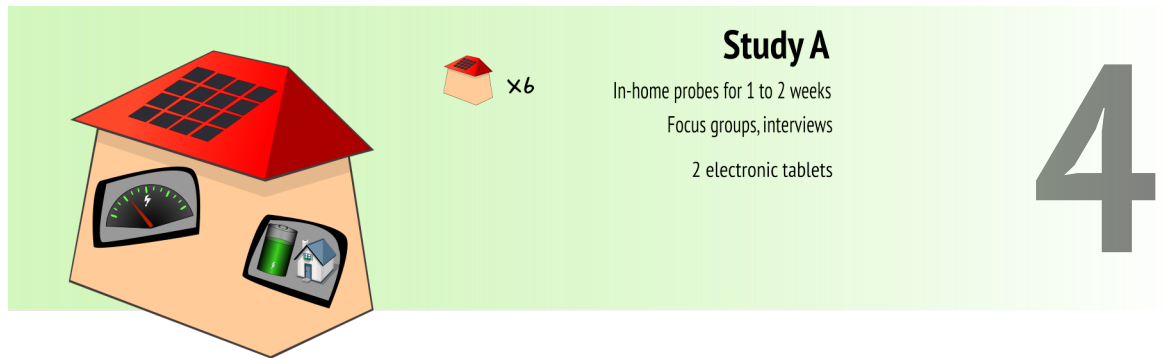
The washing machine, an Indesit Hotpoint, had been certified to industry standards. For safety reasons, the washing machine should not be switched on remotely to ensure the machine is in proper conditions to do so. During our interventions we fixed a computer tablet next to the machine so the participants could only access our system from home. This washing machine also came equipped with a child safety lock. During the phase where we were giving participants more fine-grained control over the precise timings for their washing machine, the user continued to have the ultimate responsibility for starting their machine locally, avoiding issues such as children being locked inside the machine. The electronic tablet that we used during the study to provide advanced control of the machine did not actually alter the washing machine functionality. Furthermore, the algorithms that we used about weather prediction and suggested times for washing were experimental. In the worst case, some participants could have been advised to start their washing a bit later or earlier than they would have liked – or the wash could have been done slightly cheaper at a different time than the one we suggested. We consider this to be a potential minimal inconvenience but not a risk of harm, and an appropriate part of the research.

The EV, a Nissan Leaf, has been certified to industry standards too. We did not use any additional devices on board, collecting data through manual trip diaries and the standard Carwings telematics, a service proposed by Nissan for monitoring the car.

Finally, in both studies the qualitative and quantitative collected data were sensitive, providing high resolution detail on the householder's everyday life which could have privacy implications. However, all the data have been kept on internal server at the Open University with a restricted access to the research team. A copy has been stored on EON server, as part of the collaboration. For security reasons, it is challenging to access the Open University servers from outside, even for accessing a service. Thus, we set up an external server as a proxy. As the security level of this server was lower than the university's, we were pushing but not storing live data on this external server. This allowed the electronic tablets deployed in participants' houses – running our interventions – to access live data while mitigating the risks of data being accessed by an intruder.

3.6 CHAPTER SUMMARY: A GLIMPSE ON 'HOW'

This chapter introduced the overall methodology of this project: we followed a mixed-method approach, triangulating the use of quantitative and qualitative data to address the research questions. Then, we presented the technical infrastructure available for this project through the industrial collaboration with E.ON. Finally, we briefly described the type of data and evaluation we performed. We will present each of these research steps in more detail in their respective contribution chapters.



Exploring the Connection between Consumption and Local Generation

A Technology Probe Study

‘Creativity is just connecting things.’

STEVE JOBS, THE WIRED INTERVIEW ‘STEVE JOBS: THE NEXT INSANELY GREAT THING’, FEBRUARY 1ST, 1996

Our research objective is to understand Demand-Shifting practices in the context of domestic solar electricity generation. These practices are hidden, part of people’s daily routines, especially for very common activities such as doing the laundry, making them both difficult to observe for the researcher and challenging to explain for the householders. Furthermore, we also want to explore the potential of ubiquitous technology to support or enable Demand-Shifting in households with solar generation. However, information about this local generation is not normally available to people and when it is available it is usually in a very abstract form. It is thus difficult for householders to reflect on technology they do not have. In this Chapter we present Study A, using a Technology Probes approach to help participants to talk about their daily routines in the context of technologies providing information on local generation.

4.1 STIMULATE CONTEXTUAL FEEDBACK: TECHNOLOGY PROBES

The idea of using design probes approach is to introduce a concept in a specific context, as a way of collecting qualitative data about people’s subjective experiences. We detail this approach and our implementation.

4.1.1 APPROACH

Gaver introduced the concept of ‘Cultural Probes’ as a user-centric approach to open discussions between the designer and the users, where a probe is designed to elicit user reactions and inspirations. An example is the Dream Recorder (Gaver, Dunne, & Pacenti, 1999) which participants used at home, and upon awakening they

were invited to talk about their vivid dreams. These probes required many interactions (take picture, talk about a dream). While a cultural probe acts as a behaviour sensor, a Technology Probe is an instrument that is deployed to find out about the unknown (Hutchinson, et al., 2003) and also aims to measure potential device integration. Hutchinson and colleagues studied communication patterns in the family through a Technology Probe approach (Hutchinson, et al., 2003). They implemented a fully functional stand-alone ‘Message Probe’. They see technical testing as part of the approach and mention minor technical issues during the experiment without impacting on the results.

The residential context cannot be simulated in a laboratory and therefore field studies are necessary to understand people’s attitudes to generating energy at home. These field studies have to blend as much as possible in the scenery to be visible without transforming the actual situation. Thus the Technology Probe approach fit with our requirements. In our case, the probe has to be different enough from everyday life at home to attract and put questions to householders but not so different from their routines that it disturbs them. Through this method, we can address such questions as: What are the needs and desires of users in a real-world setting? What are the effects and the effectiveness of a technology in a new environment? How can they drive users and researchers to think about new technologies and initiate new concepts and ideas?

4.1.2 PROTOCOL

We started our exploration by attending (as an observer) focus group meetings and individual interviews organised by E.ON, for the 75 participants of the Thinking Energy trial. We used video recordings and written transcripts to analyse the discussions with respect to concerns, attitudes, perceptions, motivations, and requirements of participants. The wide range of participants drove the discussions into various topics including technical problems, people’s experiences during the trial and ideas about novel technologies. These focus group and interview activities allowed participants of the E.ON trial to exchange their views about their own electricity generation and electricity consumption. Participants were invited to give feedback on the tested technologies deployed by E.ON for the purpose of the trial. Additionally, they were participating in activities allowing them to express ideas and creativity about domestic energy. Successive focus groups with the same participants brought the benefit that people get to know each other and they were more likely to talk about their experience.

Insights gained from the focus group meetings informed the design of our technology probes: a set of interactive displays showing energy data and controls to stimulate the discussion. We installed these probes at the homes of a small number of specially selected participants. The objective was to blend them in the home landscape to collect user feedback while observing energy display features. We let people explore their own attitudes, understanding, experiences and opinions about micro-generation in the comfort of their own home, without researchers being present. Our engagement with participating households comprised four steps as follows.

STEP 1 – Recruitment

We selected six participating households, including four households from the Thinking Energy trial and two households selected through informal contacts, such as friends and neighbours of the researchers (**Table 4-1**). Four of the six households had solar panels fitted – within the last 6 to 24 months of our study – and two households were actively contemplating doing so and had done much background research into the issues. The six households were all middle to upper-middle class households, with different family structures: some without children, some with teenage children or children who had left home. In total a group of twenty participants were involved, spread out over six households. We note indexes of participants H2_{WM} (WM for washing machine) and H6_{EV} (EV for Electric Vehicle) to distinguish them as they participate in other studies in this thesis.

Table 4-1 Technology Probes study – Participating households.

	Household set-up	Solar power
H1	Two parents with 3 children aged 13 to 17	3.7kwp for 18 months, 20% reduction in bill
H2 _{WM}	Two parents and one 14-year-old child	2.7kwp, for 4 months, 27% reduction in bill
H3	Two parents and two children aged 17 to 19	Considering installation
H4	Husband and Wife (scientist)	3.3kwp, for 9 months
H5	Two adult females	Install pending
H6 _{EV}	Husband (scientist) and wife with occasional visiting grandchildren	1.9kwp for 6 months

STEP 2 – Installation visit: delivering the ‘probe kit’

We composed our ‘probe kit’ of two iPads implementing our designs, as well as supporting materials such as audio/video recorders and sketchbooks so that participants could capture thoughts and ideas. One iPad was showing information about electricity production and consumption of the house as a whole. The second display referred to one specific appliance – the washing machine. Participants were invited to place the iPads in locations where they felt they would be most useful to them. We did not specifically indicate where this

should be, but did suggest that the one relating to the whole house production and consumption should be in a place where all members of the households would have easy access to them. The display relating to the washing machine was to be placed near the washing machine. We offered the possibility to stick the display on any wall with damage-free hanging Velcro or provided a stand.

STEP 3 – Week-long immersion

After installation of the probes, we asked participants to ‘live’ with them, i.e. to observe and use them and to contemplate their meaning and purpose. The main idea of the method relies on the participants living at least a week-long period immersed with technology probes without the presence of researchers. We provided a rudimentary explanation of the context and objectives of the study in written form.

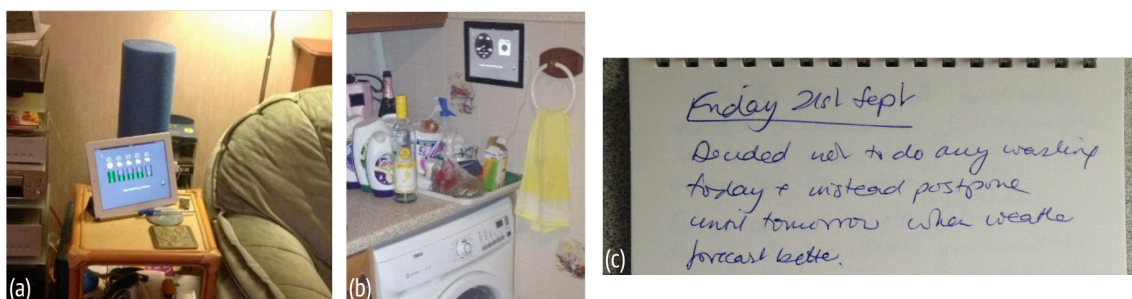


Figure 4-1 Probe kit in situ. a: in the living room, b: near the washing machine, c: H6's textbook extract 'Decided not to do any washing today, instead postpone until tomorrow when weather forecast better.'

STEP 4 – Debriefing interview

A week later a debriefing session took place at the home where we sat down with inhabitants to go over the collected materials (sketches, recording) and to discuss the users' experience. We prompted participants to reflect upon their experience with the probes and recollect discussion that took place in the household during that week. We recorded each home visit was recorded for later transcription and analysis.

4.2 DESIGNING THE PROBES

For our technology probes we used a set of custom-designed interactive displays that provided participants with seven different data visualisations and user interfaces related to micro-generation (**Table 4-1**). The design of the probes was purposefully kept incomplete and rudimentary: rather than as design endpoints that participants were supposed to criticise, they were intended to spur freewheeling discussions and collaborative exploration by members of a household.

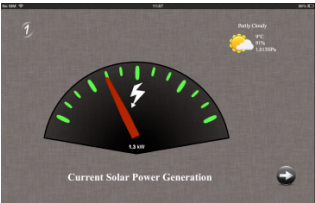



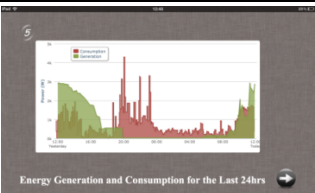
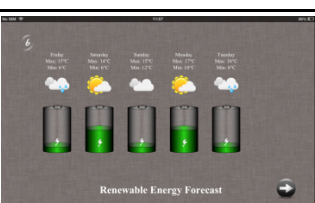
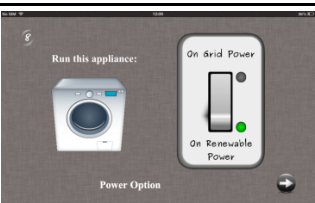
Probes	Explanation	Metaphor	Focus	Issues that this probe raises
	a. Dial A probe that displays the amount of currently generated energy.	Analogue Dial	House – currently generated electricity	Probe focuses on momentary availability of electricity (here and now), and peak production. It deliberately makes it difficult to see temporal fluctuations in electricity generation.
	b. Battery (House) A probe that conceptualises a house as a (virtual) battery that can be charged and drained.	Battery	House – Available generated electricity	Probe focuses on near term availability of electricity. Introduces temporal aspects: How long does it take to 'charge' a house? How long does a 'charge' last?
	c. Battery (Appliance) A probe that conceptualises electricity as being available or reserved for a particular appliance	Battery	Appliance – Available generated electricity	Probe focuses on everyday tasks such as doing laundry. Moves away from whole house issues to appliance-level issues. Uses relative electricity measures (full-empty): Can I use this appliance now? Raises questions about future availability: If not now, when will I be able to use it?
	d. Potential Appliance usage A probe that indicates how often an appliance (for example, a washing machine) can be used before the available energy is used up.	Analogue Dial	Appliance – Potential tasks	Probe focuses on everyday tasks and moves away from abstract electricity quantities. It relates electricity to family life and accomplishing everyday tasks: 'Can I get my washing done?' 'How often can I use the washing machine?'
	e. Generation and Consumption A probe that visualises the gap between electricity used by a household and the electricity generated by the house.	(graph)	House – total electricity generated and consumed by a household	Probe focuses on two issues: 1) the fact that there tends to be a gap between the amounts of generated and used electricity; 2) the fact that energy generation fluctuates over time. Discussions around this probe might highlight questions such as: 'How large is the energy gap?' 'How can we minimise the energy gap?' 'What factors influence electricity generation?'
	f. Energy Forecast A probe that visualises expected future electricity generation.	Weather forecast	House – Potential tasks	Probe focuses on future availability of electricity. Highlights temporal fluctuation of energy generation: 'How much electricity will we generate tomorrow/next week?'
	g. Switch A probe that allows users to decide how an appliance is powered: from grid power, from self-generated power, or from both.	Switch	Appliance – Electricity source	Probe enables users to decide the electricity source of individual appliances and thus enables them to use generated electricity for a particular purpose: 'I want to use my electricity for doing laundry.' 'This task is important to me. I want to use whatever electricity is available (i.e. grid and renewable)'. Implicitly enables users to express priorities, importance or values. 'Only enable this appliance if there is enough energy available.' 'Enable this appliance regardless of availability of negated electricity'.

Figure 4-2 Technology Probe Interface.

The design of the probes explored several dimensions:

- The amount of energy a household generates: We used metaphors such as the dial or the battery to represent abstract, concrete, absolute and relative quantities.
- The locality of energy: whether energy is available for the whole home or dedicated to specific appliances and uses.
- Interactivity: some displays simply visualise energy production while others allow users to influence how this energy is used in the home.
- Temporal aspects: Some displays explore the temporal dimension of production and generation while others focus on momentary available energy.
- Future technologies: Some displays assume technology that is currently not available in homes. In particular, we explored issues around domestic energy storage.
- Environmental conditions: some displays featured icons representing current or forecast weather (**Table 4-1a** and **f**).

In this study we used semi-functional technology probes: the displays exhibited realistic data and behaviour but this behaviour was scripted and unconnected to the existing energy infrastructure in the participants' household. This was necessary because data feeds provided by the energy company were unreliable and incomplete and because some probes visualised data that assumed not yet existing technology (notably energy storage). Thus, this study did not involve the deployment of sensors nor batteries but relied on virtual concepts display on an electronic tablet. To minimise discrepancies between energy displays and real world we created realistic simulated data by using historic data from an existing yet unrelated home and by harvesting live data feeds (weather and solar PV electricity generation) from other local sources. The iPads were only loading two web pages – whole house feed and appliance-specific feed – common to all the participants. **Figure 4-1a** and **b** shows examples of Technology Probes deployment.

4.3 FINDINGS: LOCATION AND ABSTRACTION

Our analysis of the debriefing interviews with the six households showed a general high level of engagement with the probes and lively family discussions during the week-long installation. Some individuals had clear favourite displays that they would return to often to look at, pointing it out to other members of the family, while other displays had puzzled them. Most participants had rather enjoyed the idea and look of the shiny

iPads in the house although they were also worried that the iPads themselves were consuming electricity (in fact this is negligible). In most households there had also been clearly one or more individuals who had interacted with the displays more than the others – comparable to people taking the roles of home technology drivers versus passive users in Mennicken’s study on people living in smart homes (Mennicken & Huang, 2012). Furthermore, visitors such as the children’s friends or grandchildren took a keen interest in the displays and were eager to report their opinions to the researchers.

Some people were not sure how long the interest would be kept up for such displays mentioning – ‘*after four days we didn’t notice it any more*’, or ‘*the girls didn’t even look up to ask what they were, they’re so used to all this technology...*’. But this would be argued against by others saying ‘*I loved walking through the room, and then the display would change, and it would just catch my eye, I’d see it just out of the corner of my eye...*’. People were eager to discuss their habits, and discussions went well outside the precise discussion of the displays themselves, and reflected on their own awareness of electricity consumption as well as production. Below we present our findings as a set of themes related to electricity generation in the home: (i) locality, (ii) information detail and (iii) level of abstraction.

4.3.1 LOCALITY

All the participants had placed the ‘whole house’ displays on the wall or on the table nearby to where they shared meals. All households were happy about this location – feeling that this was the best place to see it, discuss regularly and where it would catch their eye in a natural way:

‘Having it next to the table is definitely the best place. That’s where we are spending most of our time together, and talk about things. Probably on the wall, rather than directly on the table ... Having it on this table is good – we always put our cups of tea and coffee here, so you look at it the whole time, and then yes, we’d talk about it.’

The location chosen for display for the washing machine turned out to be more varied. Most participants had either placed the display directly on top of the washing machine or as close to it as possible, but in one household the washing machine is hidden in the garage. They felt that to have better use of the display they should put it in a location where it could be seen, hence they put it upstairs, next to the laundry basket, where dirty laundry gets collected. This variety in locations brought out interesting points of discussion – where some participants felt it was a good idea to have the source of electricity displayed immediately near the washing machine, imagining how at some point such a display would be an integral of the washing machines:

'I think the washing machine can also be displayed on the one in the living room [showing whole house generation/consumption]. By the time you've walked to the kitchen to look at the washing machine, you've made the decision. So having it in a central place, gives you a better idea on planning when to use it.'

For H4, the issue of having several displays and where they should be had been bothering them much – and was the first thing they mentioned on being interviewed:

H4: 'It was too much to have two things! Too much of a faff. I would always look at the kitchen display [showing whole house generation/consumption], which had certain amount of information – and then I'd look at the washing machine display [in the utility room], which had other information... and then I'd decide whether to do a load, and then I'd do it. So there was no point, from my point of view, of having two things - I would have preferred to have it all in one place. All the information there. The only thing I can imagine being useful next to the washing machine would be the switch – to say it is going to be on generated or on the grid. But ideally I'd have one display...'

So it would seem that location and energy use are concepts that are intertwined in interesting ways. The energy can be associated:

- With the particular device – i.e. at the location of the washing machine;
- With where the planning, and thinking about various jobs in the house takes place, such as the central dining room table or some other central place, or
- With the place where the appliance resides – i.e. here the dirty clothes. The dirty clothes can be some way away from the washing machine, or the planning place.

There is currently a lot of interest in designing new interfaces for appliances. Although numerous people have reported on how appliances may require novel displays to take account of different usages, and to influence through different default setting (Pierce & Paulos, 2012) most of our participants felt that centrally visible information was more important than presenting information near the relevant appliance.

4.3.2 THE RIGHT KIND OF INFORMATION

The displays aimed to create an awareness of generated electricity: how much there was, how much there was in comparison with how much was being consumed, and how much useful work (e.g. washing machine loads) could be done with the excess generated energy. In the conversations we tried to get a grip on how well people felt the displays served their needs in terms of information: was this the sort of information they wanted? Regarding the display that showed 24-hour consumption and production combined graph (**Table 4-1b**) participants in H1 felt that:

H1 (wife): 'Yes, it would be useful to have that information. Yes, at the moment I do have that information, but I need to go to the garage to see it. But it would be useful to have it in the kitchen to see it clearly. That would be useful.'

The participant is actually referring to the simple LCD reading on their DC to AC grid-tied inverter which converts DC power from the solar PV to AC power for the home (usually installed in a loft or garage as it is not intended for consumer interaction). It has the ability to display how much electricity has been generated in total for that day as well as the current generation level but it cannot display the electricity being consumed or exported, so this participant had a misunderstanding about the data available to her. However, later she reflects on what the precise benefit is of having this information displayed, and whether they would be more informed:

H1 (wife): 'if you look at that picture, it does map closely to the picture you have in your mind. You know, that in a lot of big households most of your consumption will be during the evening and into the dark hours. And you know roughly when your energy is being generated. So I don't think that having a picture can change that – you have that picture anyway. And I think if I asked the girls – if you asked them – draw me a picture, of when you think we are using, and when we are consuming, I think you would get this picture. It would be quite accurate. But it is good to have this picture.'

Here the participants are reflecting on the models they have – themselves – of their own energy behaviour. However, what is interesting is that we know that much of that information is not actually available to them, as the precise levels of electricity generated are determined by the precise roof and cloud coverage that day. One of the displays (**Table 4-1a**) showed the currently generated amount of solar power:

'That display an instant, or relatively quick, we think..., display of the amount of sunshine, which is interesting in its own right, but it doesn't add anything beyond looking out of the window!'

Clearly this participant felt that he had sufficient information to be able to make informed decisions – and that using common sense was sufficient. Looking out of the window, seeing the sun shining, should be enough information about the amount of generated information. However, as we outlined earlier, this is only a rough indication of the amount of electricity potentially being exported or spare. In the focus groups for the wider trial, people discussed a need for more precisely knowing what they can do with the generated electricity. *'If I have the washing machine on, can I also do the ironing when the sun is out?'* So people's perception of the levels of information that they require in order to adjust their behaviour to maximise their energy balancing behaviour is different from household to household.

4.3.3 ABSTRACTIONS AND REPRESENTATIONS

Some of the displays we used were hinting at future technologies such as energy storage which are not implemented in any participant's homes yet. In particular, we had put forward the idea of a battery (**Table 4-1b** and **c**) – representing the total available electricity for the whole house, or representing the 'number of

washes' available or the washing machine. The battery abstraction caused the most controversy among participants, with them almost holding opposing views from each other. In H1, participants were concerned about this display, as it appeared completely wrong to them. When we explained it was meant to be imagined as a future technology, the reaction was:

H1: 'It's interesting, because I didn't realise that was now a possibility. We were very early on adopting the solar panels. But one of the first things I asked the guys when they installed it, was where the power was going to be stored. He seemed very surprised about my question. So it's good if you think that is moving forward...'

The participants appeared to be struggling with imagining future scenarios with novel features. In contrast, the participants in H2_{WM} were quite happy to imagine the scenario – also knowing that they may have an opportunity to have the technology installed in a few months as part of the wider Thinking Energy trial. One member of H2_{WM} particularly liked the battery icon, 'because of its simplicity'. On the other hand, for the participants in H6_{EV} it was an almost useless notion: 'We didn't quite fathom this one ...' and in notes written for day 2:

H6_{EV} – Textbook: 'Discussed washing machine display with wife, but can't convince her that a real 'battery' storage would be of any use to us. Failed, probably because I'm not convinced myself. In future, could the display be used so that if enough solar energy had been accumulated in the battery it would automatically start the washing machine?'

So although the participants in H6_{EV} had grasped that the idea was to think of a future possibility they could not see its usefulness – unless it was tied to automatically starting the washing machine, whereas without this possibility:

H6_{EV} (husband): 'At the moment, an empty battery would show me that we'd have to wait to run the dishwasher till the battery is recharged. Well, there is no benefit for us having to do that. Whether in the future there'll be benefit to that I don't know....'

This view – of there not being any benefit in 'having to wait' – was not echoed among other participants, most of whom considered this to be a plausible and appropriate behaviour. In H4 participants were keen to explain how they do their planning – partly referring to the weather forecast displays, but also partly explaining how they do so at the moment anyway. This was the only household with a special generation meter that was displaying currently generated power, on a handy display in the kitchen.

H4 (wife): 'I might think, OK, I'll wait till it goes up to 2kW, before I put the washing machine on, because I know the washing machine uses about 2.5 kW at its peak consumption... So if it looks like a sunny day, and I think it will get up higher, I will wait till lunchtime, because that's when it might be at that point. If it looks sunny in the morning, and it looks like it will get foul in the afternoon, I might put it on in the morning, knowing that although it won't cover the peak consumption period, I get more out of it. So trying to work out

what the weather is doing at the moment, what's going to happen later in the day, later in the week, how much you're getting and what the best time is to put it on...'

And then continuing to reflect on what the battery display might add to this process, she reflects on the additional pieces of information she needs to make a balanced decision:

H4 (wife): 'Part of the problem is; you don't know how much is being used by other things. We got these smart plugs – but it's too much of a hassle to go upstairs to the computer, and go to the website, and work out what everything is consuming... and then adding it all up, and subtracting it from what you are generating, and by the time you've done that – the sun will have gone in anyway... So you need something instantaneously...so If we have the battery – that would be ideal. I could see, OK I have enough so that I can do about two washes... that would be great'.

Although this participant was someone who considered herself being comfortable with figures (being a scientist), and would always want to see concrete numerical representations – she did not voluntarily criticise the lack of numbers on this particular display. Whereas this was a complaint from a number of participants:

H2_{WM} (husband): 'The battery one for the house as a whole is lacking some kind of unit – you don't know what full means, or two /third... Whereas the battery with the washing machine works better – because I can imagine that it refers to a certain amount of wash loads.'

In common with others, this participant couldn't imagine what a half-full battery might correspond to. Interestingly, the participants from H5 could also see an additional side of the potential of this metaphor: *'just like battery on phone, I get used to it.'*

4.4 DISCUSSION

The interviews revealed a few insights that are important for the design of information technologies related to micro-generation.

4.4.1 MICRO-GENERATION DOES CHANGE ELECTRICITY CONSUMPTION BEHAVIOUR

There is clear evidence that the mere presence of micro-generation in a home make people question their electricity consumption behaviour and in many cases makes them adjust their behaviour. Some engage on concerted efforts to shift demand to times of peak generation while others alter their habits in a less directed way. Thus the impact of micro-generation lies not just in the electricity that is generated but in the ability to use micro-generation to motivate people and to change their view of themselves from being a passive (even informed) consumer of electricity to an active participant. It highlights that digital technology should focus on creating opportunities for people to adjust their behaviours rather than simply informing them about the state of electricity generation in the home. Furthermore, digital technology should be designed to support people's changing perception of themselves as active participants and energy custodians rather than supporting a self-

image of a smart and informed consumer. These findings reflect the early evidence highlighted in the literature (Keirstead, 2007; Pierce & Paulos, 2012; Dobbyn & Thomas, 2005).

4.4.2 PEOPLE BELIEVE THEY KNOW, BUT THEY DON'T

Although this was a highly motivated group of individuals, who had really looked into the whole energy generation angle there were many misconceptions about how the amount of generated electricity, how generation is influenced by external factors and whether they have the right and enough information to correctly understand things and what kind of information they might need. For example, most people felt familiar enough with the graph display which shows periodic spikes. Most people wanted to see more details and be able to work out exactly when the spikes occur. However, the narrow spikes are almost meaningless for getting a sense of the amount of electricity generated. More importantly, some people believed they had a good understanding of how to estimate current generation when in reality they didn't. Looking out of the window is an unreliable means of determining energy production as seasonal variations (height of the sun above the horizon, shading from leafy/leafless trees, see **Figure 4-3**) can have a tremendous influence. It highlights that digital technology should be designed to help people form an appropriate coherent model of micro-generation, not just inform about individual aspects such as current generation. One way of doing this is by using metaphors that help people understand their role with respect to micro-generation, in the same way metaphors have enabled laypeople to make effective use of computers.



Figure 4-3 Estimating solar generation is not as easy as we could think (H_{2wm}). Location, orientation, tilt, shading from trees, weather, etc. are many variables impacting on the generation

4.4.3 THERE IS A WIDE VARIATION OF HOW AND WHY PEOPLE ENGAGE WITH MICRO-GENERATION

Within this group of highly motivated people there was still a wide variation as to how far they were prepared to go in terms of making adjustment to lifestyles to meet the energy balance. For some people the fact that delaying one action only saves 30p (by using excess PV energy) is not worth it – for others there are other

motivations beside the monetary value, that make them go the extra mile. As with Pierce and Paulos (Pierce & Paulos, 2011) we found a wide range of motivations for engaging with energy. There are those who are keen to think of all of the minute ways in which they can adjust their behaviour – like cooking during the day, when the sun is out, rather than wait till the evening, or buying an electric lawnmower instead of petrol – versus someone else who says *‘but that battery won’t mean anything for me, because there is no advantage!’* (H6_{EV}). Conclusion: There seems to be the potential to design specialised solutions for specific subgroups of users of micro-generation. However, while we have some rough understanding of possible subgroups (for example detail-oriented versus whole issue oriented) we have no understanding of the specific technology requirements of these subgroups. Rather than looking for a single generic design approach it might be better to focus on each subgroup separately.

4.5 REFLECTION ON THE TECHNOLOGY PROBES METHOD

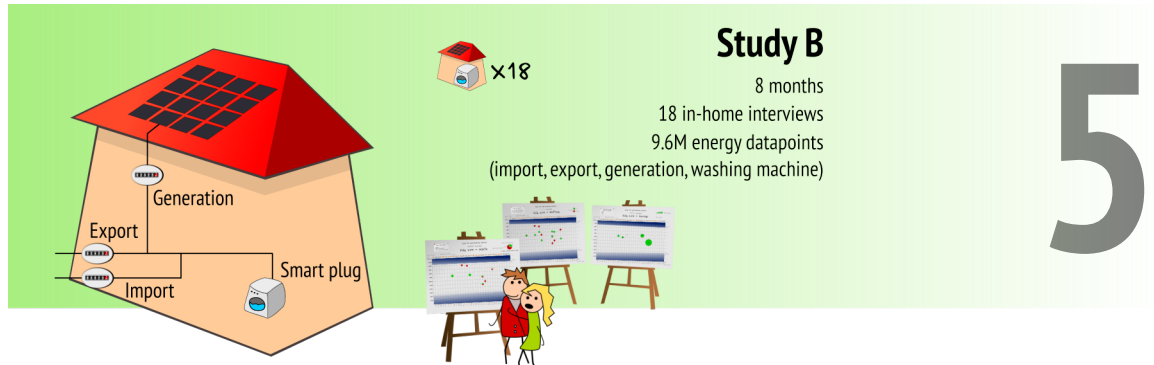
To limit the ‘study’ effect, we collected user feedback through one interview, conducted at the end of the experiment period. In contrast with other studies we did not provide a list of tasks to do, cards with questions to answer or other ways requiring participants to undertake any extra effort. This is because we wanted to keep the researchers’ presence and visibility to a minimum. Unfortunately, none of the participants had felt comfortable enough to video themselves. However, some participants took rich and precise notes about what they observed, understood and things they had done. They were also able to describe their daily routines about appliance uses and energy habits. This points out that probes were blended in the background but visible.

Some participants had difficulties imagining ‘electricity availability’ – represented by a battery level like laptop or smartphone – without a physical battery in their garage. This point underlines the technical difference between our study and Hutchinson and colleagues (Hutchinson, et al., 2003). The communication probes they introduced were stand-alone products, which could be placed in the house and would work – while our energy probes, to be fully functioning, would need to be part of the fabric of the house. Our probes were enough to help participants reflecting about local electricity generation and domestic consumption with much less engineering. Furthermore, while Hutchinson’s probe provided interactivity, we wanted to observe how our probes were able to blend into the domestic environment.

Participants needed to imagine the probe being integrated in their everyday life. During our study we chose tablets to deploy our energy prototype features easily. In an actual implementation, these energy features would be displayed directly on appliances (i.e. washing machine LCD) or integrated on an existing screen in the home. One issue participants reported was that they worried the display itself was too bright at night or used too much energy as it was on all the time. This worry seemed to distract them from being able to imagine such features as part of future product design. The user feedback can be easily affected by technical issues or aesthetics which draw the user's attention to them and reduce the emergence of creativity and ideas. Nonetheless, several participants came up with creative ideas about the location of the probe and the use of this new 'energy information'. For example, a participant suggested placing our probe in the corridor above the laundry basket rather than near the washing machine, far away in the garage.

4.6 CHAPTER SUMMARY: MOTIVATIONS FOR A DEEPER EXPLORATION

This chapter presented our initial step into the exploration of the relationship between local solar generation and electrical appliance usages. Our findings reflected the literature, showing local electricity generation impacts on energy behaviours and practices. However, it requires much deeper insights to clarify them. Participants have misconceptions about how much electricity they generate and when. We emphasised the need for deeper investigation into the relationship between consumption and local generation. Finally, the participants particularly appreciated the feature showing the electricity generation forecast. They were used to planning their next few days based on the weather forecast and their solar electricity generation forecast was given a place in their daily routines. Looking ahead appeared as a key feature in the context of local electricity generation. The conclusion of our exploration study resonates with the existing literature and drafts insights on digital requirements in the context of domestic micro-generation. Digital technologies can potentially play a role in helping people become more effective 'Demand-Shifters'. However, the design of digital interventions is made difficult by our limited understanding of existing energy shifting behaviours, our limited understanding of the adjustability of domestic energy consumption, our limited understanding of the constraints that various life patterns impose on Demand-Shifting behaviour and the sheer breadth of available devices (smart meters, mobile phones, smart plugs, smart lighting etc.). In the next chapter, we build a detailed view of the domestic energy ecosystem in the context of local solar generation. We particularly focus on the connection between the washing machine electricity consumption and the local solar electricity generation.



Understanding Demand-Shifting Behaviours

A Participatory Data Analysis of Laundry Routines

‘Difficult times disrupt your conventional ways of thinking and push you to forge better habits of thought, performance and being.’

ROBIN S. SHARMA, *THE LEADER WHO HAD NO TITLE*, 2010

One of the main aims of this thesis to understand how householder’s routines consider local solar electricity generation. We also ask, how does Demand-Shifting fit in this context? We conducted the study B to investigate more precisely how household members were carrying out the process of manually shifting their appliances. What were their struggles and constraints when aiming to maximise their self-consumption? How good were they at manually doing this, and what scope is there for further improvement?

We used the washing machine as a starting point of our exploration. A typical modern washing machine uses a modest amount of electricity and thus shifting laundry behaviours only promises small savings. In fact, we will emphasise that washing machine consumption represents less than 2% of the overall electricity consumption. However, prior studies show that people already adjust laundry behaviours ‘to catch the sun’ (Kobus, Mugge, & Schoormans, 2013) (Pierce & Paulos, 2012). Furthermore, most households²⁴ (96% of households in the UK, 2011) have a washing machine, and doing laundry is an activity that is strongly influenced by social norms (about cleanliness) which can hardly be neglected (Shove, 2003). Doing the laundry depends on external temporal constraints (the need to have clean clothes ready for work or school), and it is (often) a collaborative activity that requires communication between family members. We thus see doing the laundry as a prime subject for investigating technological support for domestic energy Demand-Shifting. In this chapter we

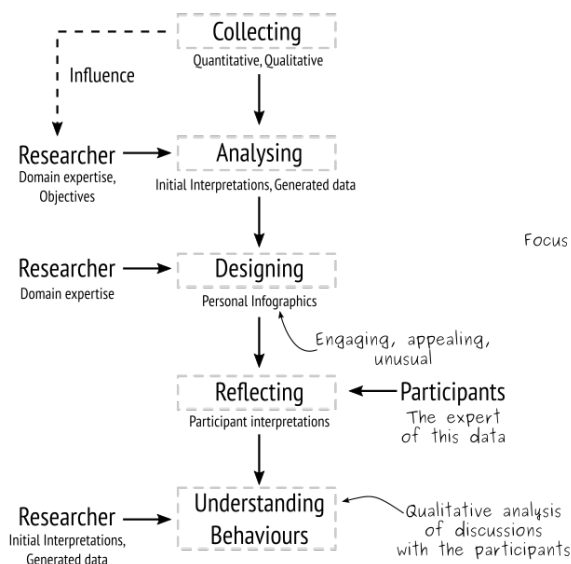
²⁴ Office for National Statistics, General Lifestyle Survey Overview – a report on the 2011 General Lifestyle Survey, Chapter 4: Housing and Consumer Durables, 4.19 – <http://www.ons.gov.uk/ons/rel/ghs/general-lifestyle-survey/2011/rft-chpt-4-ref-table.xls>

introduce the Participatory Data Analysis and its implementation to improve our understanding of the laundry routines in the context of domestic solar generation.

5.1 PARTICIPATORY DATA ANALYSIS (PDA)

We designed a novel method which we call Participatory Data Analysis (PDA). The key novelty of this method is the use of personalised energy behaviour infographics during home visits to spark self-reflection among householders. This method relies on appealing infographics of personal data to help participants to reflect on their own data and to talk the researcher through their daily routines. **Figure 5-1a** presents the five steps of this method and **Figure 5-1b** shows an example of implementation with the study B.

(a) Participatory Data Analysis (PDA)



(b) Study B: Understanding laundry routines in the context of local solar generation

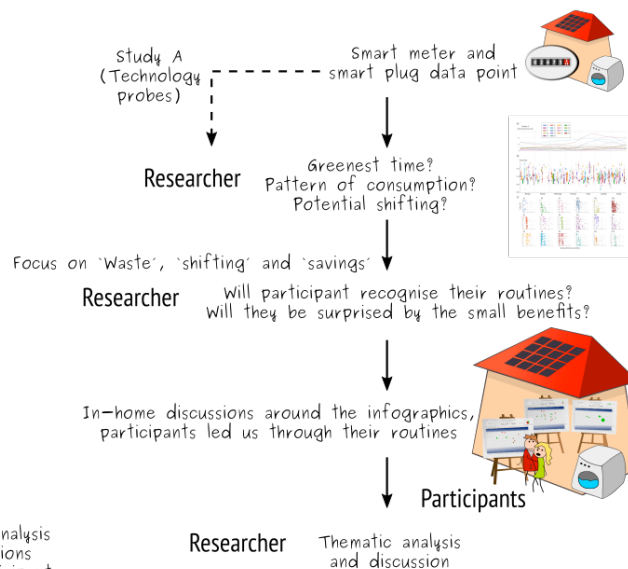


Figure 5-1 Participatory Data Analysis. a: The generic process of the PDA; b: an example of PDA implementation with study B

Here we briefly explain the main steps of the overall approach in general terms before explaining its specific implementation for the laundry study in Study B.

Collecting

The process of collecting data for a PDA is similar to a typical data collection process in quantitative and qualitative studies respectively. The key difference is about which data to collect. It is important at this stage to be as explorative as possible in the variety of sources and types of data. From the quantitative point of view, it means collecting micro information (e.g. overall energy consumption and production and consumption from individual appliances) and macro information (e.g. weather condition and forecast, grid carbon intensity). The qualitative data can mix group and individual data collection and cover the research from a few

different angles. For example, discussions with participants can mix product centric feedback with more general descriptions of habits that may seem not directly relevant to the appliance usage but are relevant in the wider context of the research, particularly since we are interested in how routines and daily are effected.

Analysing

The first step in the analysis is carried out by the researcher, influenced by domain expertise and experience from previous studies, and explores the data as a typical Exploratory Data Analysis. The main objective is to gain a better understanding of what are the data leading to an initial answer of the research question, but also identify those areas that are worth investigating in more detail. This led exploration aims to extract two types of information:

- What are the topics which dominate the initial interviews, focus groups and home visits? What are the interesting or surprising findings that stand out (e.g. trends, anomalies) from the Exploratory Data Analysis?
- What information (potentially) triggers the participant's interest?

To address these questions, it might be necessary to generate higher-level data.

Designing

At this stage, the researcher built an initial interpretation of the data through the analysis, with an understanding of *how* the studied routine takes place, for example in time or frequency. However, many questions remain about *why* this routine takes place like this. Thus, the 'designing' stage is about building infographics to encourage participant's discussions towards these questions. While there is no recipe for the design of such visualisation, infographics are likely to be successful if they are appealing, deeply personal and straightforward. In a few introductive sentences, the participants should be able to understand the infographics and start an initial reflection.

Reflecting

The next step is a semi-structured interview driven by the participants reflecting on their data. The researchers invite the participants to describe the infographics, i.e. the visualisation of their personal routines. The researchers can also bring questions into the discussion about data points they could not understand or interpret properly. Similarly to a typical exploratory semi-structured interview, the analysis can be done through a thematic analysis. While the high-level themes should be implicitly driven by the infographics, the discussions cover a wide range of more specific themes to identify.

Understanding Behaviours

In the final step, the researcher conducts a qualitative analysis of the participant's discussions. This analysis considers the raw data collected during the first step, the initial interpretations and generated data to build an understanding of the user behaviours. In the next section we provide more details about the PDA by describing its implementation through the washing machine study.

5.2 COLLECTING AND ANALYSING THE DATA

In this section we detail the two first steps of the PDA: collecting and analysing. We relied on participants from the E.ON trial and we conducted an Exploratory Data Analysis.

5.2.1 'GREENER WHITES' PARTICIPATING HOUSEHOLDS

The participating households of this study were part of the group 'Greener Whites' of the Thinking Energy trial. These 18 households were given a specially manufactured Indesit Hot Point connected washing machine. This washing can communicate via ZigBee for monitoring and control. This functionality will be detailed and used in Chapter 6. We asked the participants to dedicate an E.ON smart plug to the washing machine for the purpose of this study. This guaranteed the monitoring of the washing machine's power consumption throughout the study.

Although all participants owned their own homes they had diverse demographic backgrounds (from childless mixed and single-sex couples to large families, one or both partners employed or one or both retired) and exhibited a diverse set of life patterns (some spending most of their time at home and others spending most of the day at work). **Table 5-1** provides more details on the participating households.

Thanks to the technical infrastructure we described in Chapter 3, we collected the electricity data between June 2013 to January 2014 (eight months), representing 9.47M instant data points. This period was enough to capture seasonal variation. Before each analysis, we filtered the days containing faulty data based on a series of assumptions. These filters include for example import and generation greater than zero, generation lower than the theoretical maximum installed on the roof and the washing machine consumption lower than the overall consumption. These coarse-grain filters allowed us to automatically remove all the main faulty days of data recording.

Table 5-1 Participating households - Greener Whites

Households	People	Occupation Home/Work balance	Avg. loads/Week	PV (kwp)	W/M place
H1 _{WM}	2 adults	3 days working away, 2 days working from home	2.3	3.84	Kitchen
H2 _{WM}	2 adults, 1 child, 1 visitor	Work out	4.2	2.8	Util. room
H3 _{WM}	2 adults, 2 children	Wife at home, husband works mostly out	2.6	3.3	Util. room
H4 _{WM}	2 adults, 2 children	Both working out	3.8	1.2	Kitchen
H5 _{WM}	2 adults, 2 children	Both working out	0.9	3.9	Kitchen
H6 _{WM}	2 adults, 1 adult Mon-Fri, 1 child sometimes	About 50% in / 50% out	5.7	3.84	Util. room
H7 _{WM}	2 adults, 3 children, nanny	Husband mostly away, wife works, nanny at home instead	1.9	2.64	Util. room
H8 _{WM}	2 adults, 1 child	Wife works at home, husband works out	3.2	3.12	Util. room
H9 _{WM}	2 adults, 1 child	Wife works at home, husband works out	3.5	3.36	Kitchen
H10 _{WM}	2 adults	Mostly home	3.9	3.995	Util. room
H11 _{WM}	2 adults, 3 children	Wife in on Mon, both out Tues to Friday	3.2	3.995	Util. room
H12 _{WM}	2 adults, 2 children	Mostly at home	1	2.88	Util. room
H13 _{WM}	2 adults, 2 children, 2 temporaries	Wife works at home, husband work out	2.6	3.6	Util. room
H14 _{WM}	2 adults	Wife works from home, husband works out	2.3	2.78	Util. room
H15 _{WM}	2 adults, 2 children	Mostly home	2.4	3.84	Kitchen
H16 _{WM}	2 adults, 1 child	Wife flexible shift and husband 3-shift	8.5	2.16	Util. room
H17 _{WM}	2 adults	Retired, lot of activities outside	2.4	3.2	Kitchen
H18 _{WM}	5 adults	All working out	1.8	4	Util. room

5.2.2 EXPLORING THE CONNECTION BETWEEN CONSUMPTION AND GENERATION

In this exploration, we start with an overview and a detail view of electricity in the context of domestic solar generation. Then, we look at the connection between the washing machine usage and the local generation.

Overall Consumption and Generation

Figure 5-2 presents the average daily electricity parameters for the 18 ‘Greener Whites’ participants: overall electricity consumption (in red), local solar electricity generation (in green), exported electricity from (in light blue) and imported electricity to (in light red) the grid.

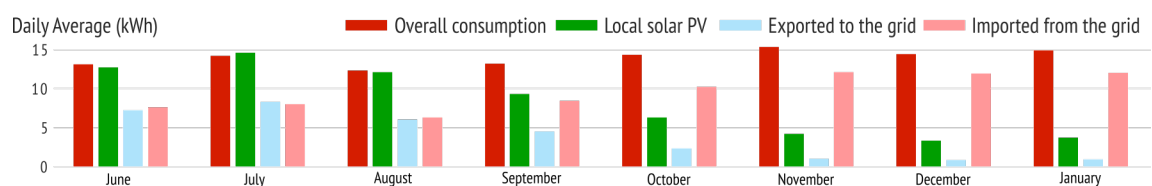


Figure 5-2 Daily average energy. Overall consumption, generation, export to and import from the grid over the months (June 2013/January 2014)

These monthly figures show that the capacity of solar generation is enough to power the entire home in summer and a significant part during the rest of the year. The generation is greater than or equal to the consumption over summer months. However, there is still a significant import from the grid and export to the grid. We cannot expect zero import from the grid because these households do not have energy storage capacity. However, it reflects the energy gap problem targeted in this thesis. More generally, based on participating households' average over summer months (June, July and August), the generation could have cover 97% of the overall consumption. Instead, 55% of the generation has been exported to the grid because it has not been used right away, at the generation time. Meanwhile, 55% of the consumption has been drawn from the grid because the solar generation was not enough at the consumption time. The domestic energy gap, at least in summer, is not about capacity but time of use. A clear objective is to find solution to reduce this energy gap and increase the proportion of the local generation as a fraction of the local consumption, i.e. to increase the self-consumption.

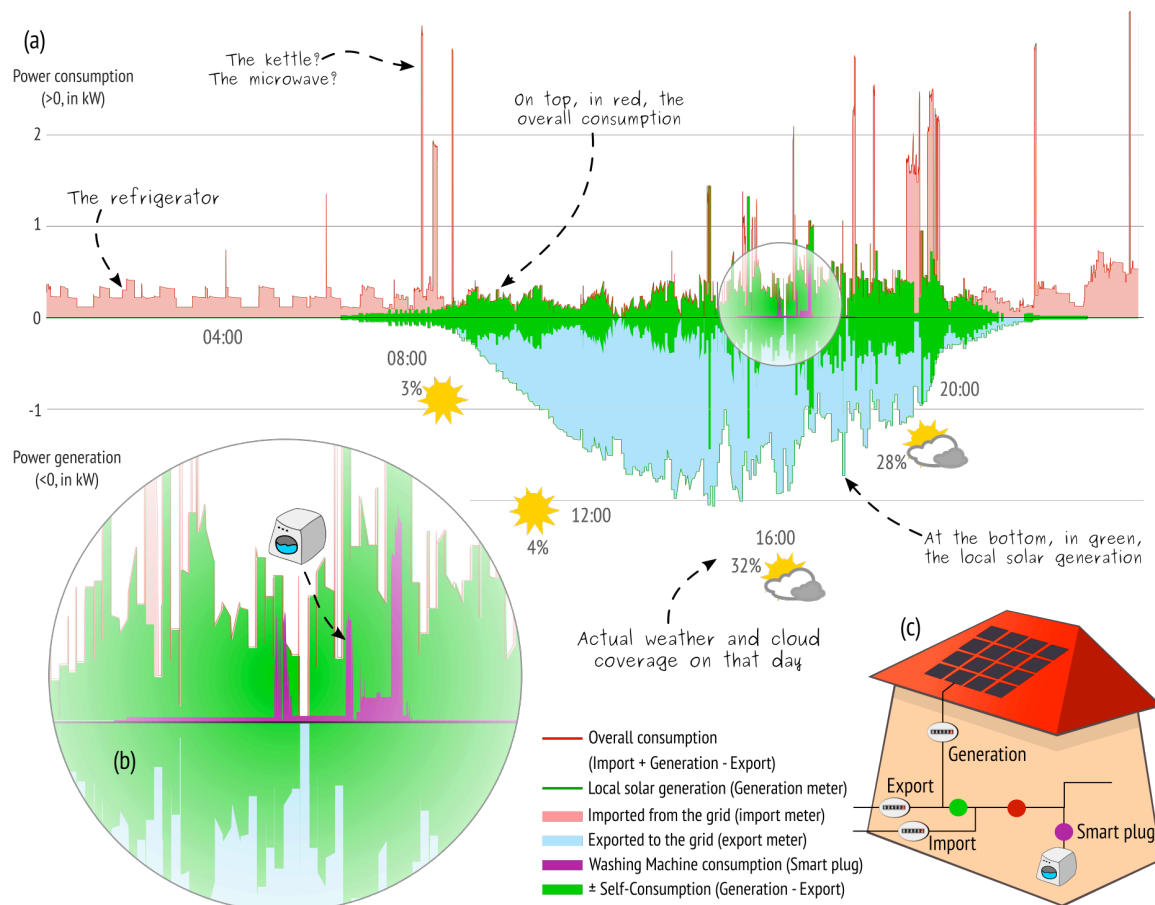


Figure 5-3 Instant power in H12WM on July 15th 2013. a: over the whole day; b: zoom in a washing machine load; c: monitoring infrastructure. Note: the self-consumption, in green, is shown twice (+/-) to be compared to the consumption and the generation.

In contrast with aggregated figures, **Figure 5-3a** shows the detailed instant power collected throughout the day on July 15th in H12_{WM}, combining data from the generation, export and import smart meters as well as the washing machine smart plug (**Figure 5-3c**). Following the same colours, we can observe the electricity consumption, the red line at the top of the import (in light red) and self-consumption (in green), depending on whether the local solar PV output, the green line at the bottom, provides enough power or not. We represent local generation and export as negative value, ‘supplying’ power rather than ‘demanding’ power. In order to compare the self-consumption against both the overall consumption and the local generation, we show this value twice (+/-). When the local generation exceeds the overall consumption, electricity is exported to the grid (in light blue). From the generation point of view, this is an average day with a peak at 2kW around 2P.M. We can observe the generation curve is noisier, reflecting the impact of the variable British weather: looking back at the weather²⁵, on that day it was a sunny morning followed by cloudy alternations on average. Each cloudy period has a significant impact on the generation.

Looking at the consumption, we can observe a base load throughout the day associated with background appliances such as refrigerators and freezers. On that day, H12_{WM} (husband) is working at home most of the day. However, there are more activities in the evening. In **Figure 5-3b** we can observe the details of a washing machine load (in violet, zoomed in), between 3P.M. and 4P.M. This clearly highlight the limited power amplitude of a washing machine compare to the generation and the overall consumption.

Washing Machine loads and Local Generation

Table 5-2 zooms into the energy characteristics of the washing machine. The average measured electricity consumption of the washing machine loads across the 18 households was 0.28kWh a day, which represents 1.82% of the overall average household consumption and 7.8% of the average daily household generation (2.7% in June against 15.1% in December). Over a period of 8 months we monitored 1960 loads (we may have missed a few during a brief monitoring failure).

Table 5-2 Washing machine consumption in relation to local solar generation a day.

	June 13	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan. 14	Average
Consumption (kwh)	0.29	0.28	0.26	0.32	0.25	0.29	0.29	0.22	0.28
% of overall consumption	2.3	2.1	1.8	2.1	1.7	1.6	1.8	1.2	1.82
From PV (kwh)	0.18	0.19	0.15	0.17	0.12	0.11	0.10	0.07	0.13
From PV (% of consumption)	62	66	59	54	46	38	35	34	49

²⁵ Percentage of cloud cover on July 15th 2013: <http://www.worldweatheronline.com/milton-keynes-weather-history/buckinghamshire/GB.aspx>

This represents an average of 3 loads a week for each household. We can observe that only 62% of this consumption came from the solar PV in June and 34% in January. There are two important points to highlight. First, the washing machine – especially the highly efficient one that we used in this study (rated A+++) – does not represent a major load in the overall energy consumption. Second, a large part of the washing machine energy (38-66%) is drawn from the grid, even in summer.

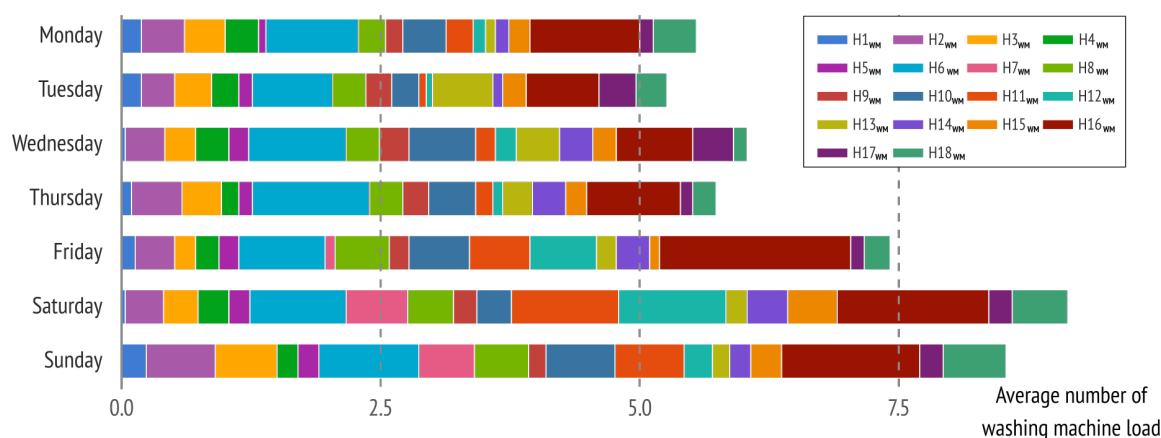


Figure 5-4 Average number of washing machine load per day of the week. Note: while colour nuances might be difficult to distinguish, we note that we ordered participants from left (H1_{WM}) to right (H18_{WM})

In **Figure 5-4** we depict the washing machine loads of all participating households throughout the week. We summed up the number of loads for each day of the week over the period and we present the average number of load for each day of the week. While **Table 5-1** presents the average number of loads per week, here we look at the distribution across the week. This suggests no specific ‘laundry day’ for most of the households. However, H7_{WM}, H2_{WM}, H12_{WM}, H16_{WM} have a significant preference for washing over the weekend. The latter has by far the highest rate, even throughout the week.

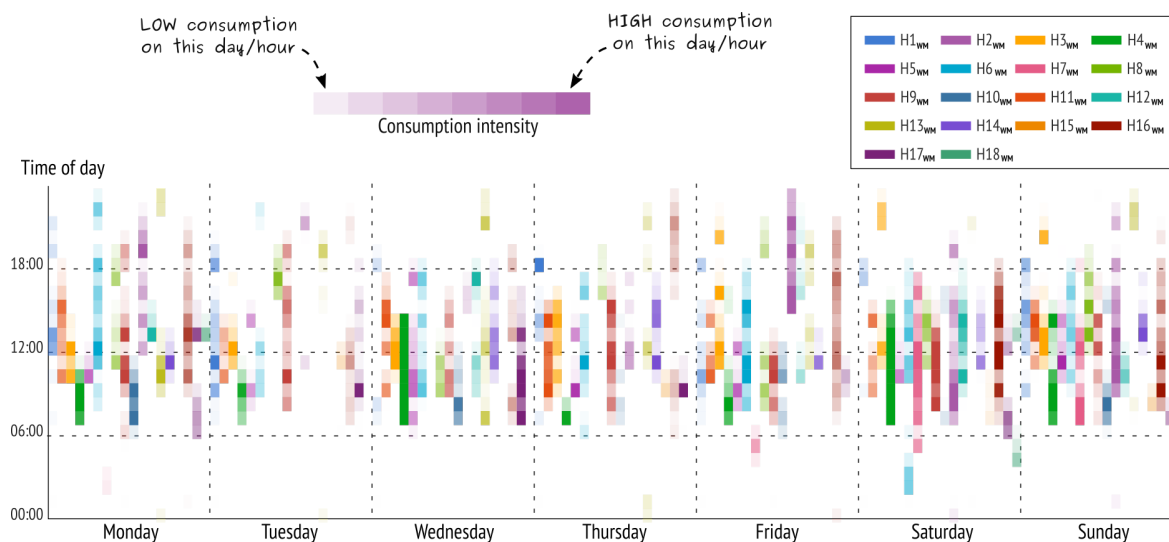


Figure 5-5 Washing machine load intensity per day of the week.

In **Figure 5-5**, we zoom in to get a view of the washing machine energy consumption across each day of the week. For each household, the strength of the colour reflects the amount of consumption. Thus, a strong colour reveals either a repeated use of the washing machine on this time-slot or the use of a wash cycle consuming more energy. We can look at this chart as multiple layers stacked on top of one another, each of them representing the washing machine consumption over one week. We observe that most of the washing machine loads took place between 6A.M. and 6P.M., roughly during day time, when there is a potential local energy generation.

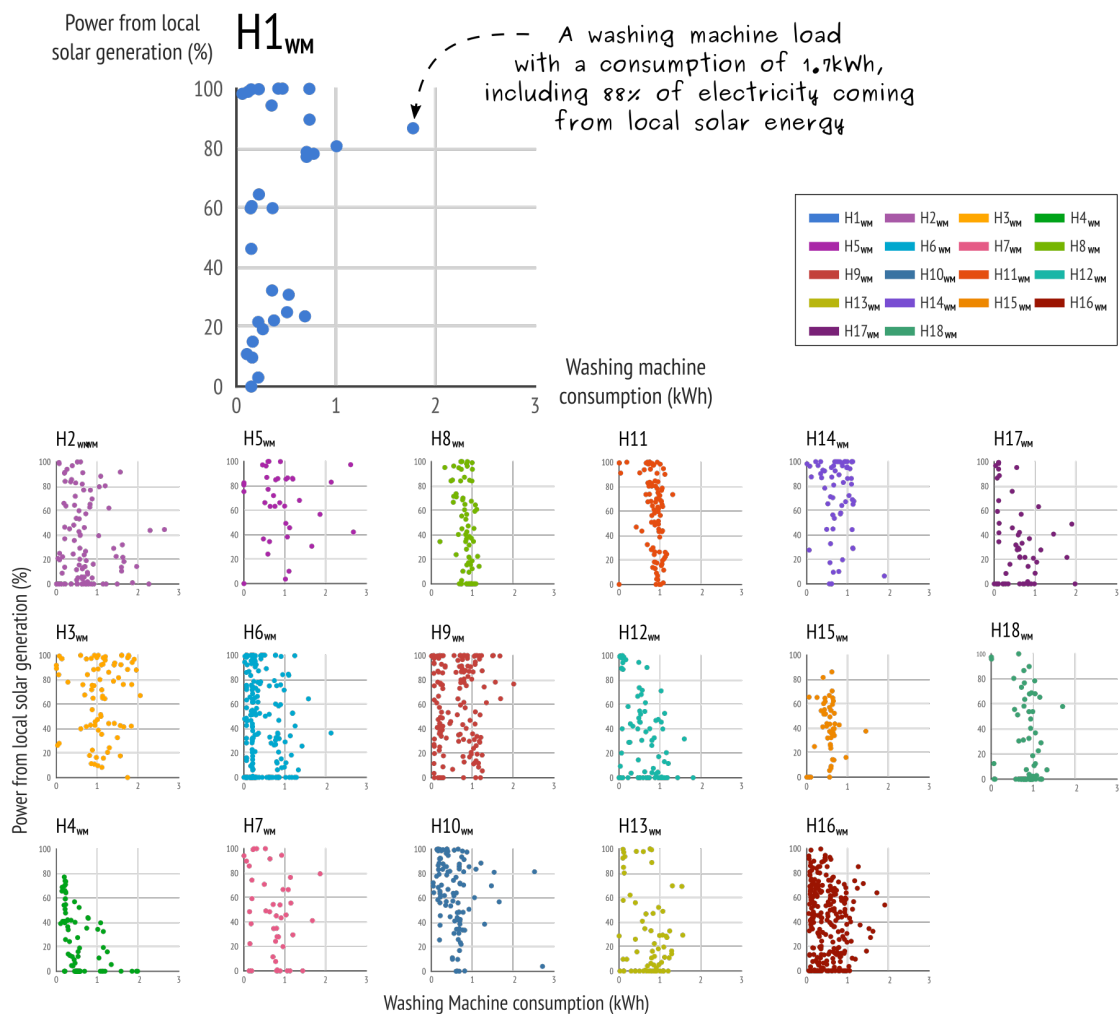


Figure 5-6 Mapping of Washing Machine and Solar PV energy in the home for each participant. a: number of washing loads per week day; b: distribution of the washing machine energy consumption during the day across the week; c: the distribution of washing machine load, consumption versus actual percentage coming out of the local solar PV.

We can connect this chart with the scatter plots in **Figure 5-6**, in which each dot represents a washing machine load. The x-axis displays the energy consumption of the load while the y-axis shows which percentage of this load has been taken from the local solar PV. This highlights the weight of the load depending on the

chosen wash cycle. For instance, H6_{WM} (light blue) has many loads throughout the week, but the scatter plot reveals a lot of these loads are lower than 0.5kwh. Looking closer to the scatter plots, we gain a better view of the ‘green’ loads – the loads powered from local solar PV electricity. For most participants the loads are well distributed between 0 and 100% of green energy, suggesting a random use of the washing machine on and out of sunny period. We notice H14_{WM} (purple) is particularly diligent, as most of the loads are beyond 50% of green energy. Also, H4_{WM} (green) has the smaller solar PV and struggles reaching 80%. These scatter plots are contrasting with the daily distribution in **Figure 5-5**, in which we observe that most of the loads took place between 6a.m. and 6p.m. Thus, doing green laundry appears more complex than simply running the washing machine during day time.

Weighting the Potential of Washing Machine Load Shifting

Extending the exploration, we present a Best Shifting Algorithm to weight the potential of shifting the washing machine load in time.

Best Shifting Algorithm

We designed a Best Shifting Algorithm to calculate the best fit in terms of shifting the load to a different time.

In this research, a *load* represents one use of the washing machine. A load is characterised by the start time, the duration and the series of data points composed of a time stamp and a power value. The *green percentage* represents the amount of electricity (kWh) used by a load that comes from the local solar PV compared to the total amount of electricity consumed by this load. Finally, the best fit of a load is the time-slot that will provide the highest percentage of electricity coming from the solar PV during a specific day.

To determine the *best fit* of each load and generate the visualisations, we designed a system which analyses the electricity data of each day through three steps:

1. Synchronisation: we collect data from heterogeneous sources and synchronise them at a 1-minute sampling rate. This includes the data coming from the import, export and generation meters and from the washing machine smart plug;
2. Load detection: we detect the washing machine loads and we store their details. Then, we remove these loads from the overall consumption to isolate the consumption of the other appliances. It is then possible to add the washing machine loads to different points during the day to evaluate their impact;
3. Shifting: a brute force algorithm tries systematically every combination of loads over the day and computes a score based on a given objective.

In this study, our objective is to maximise the self-consumption, i.e. to use as much electricity coming from the local solar PV. In other words, our goal is to minimise the overall export. The objective can be formalised as follows:

$$\text{minimize } E' = I' + G_{PV} - (C_{WM} + C_R) \quad (5-1)$$

which represents over one day the potential export E' given a potential import I' , a local generation G_{PV} from the solar PV, a washing machine consumption C_{WM} and a remaining consumption C_R . It is important to highlight that this computation is based on actual import and actual export. However, after shifting we call these two variables ‘potential’ (E' and I') because these are the values that we would have had if the washing machine load had been started at the ‘best start time’. When there are several loads, the objective is to find the combination of best start times (i.e. best position of each load) that produces the best overall solution.

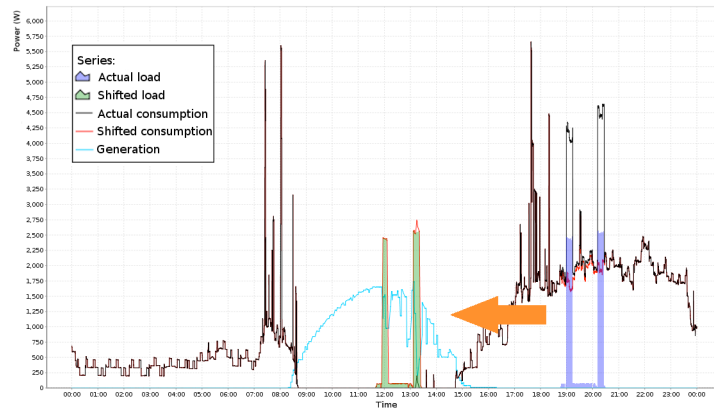


Figure 5-7 Example of load shifted from the evening to the middle of the day, at solar electricity generation time.

We implemented our system in Java and we sliced the analysis in 1-day periods. At this point the algorithm does not explore shifting towards a different day. In the event of a washing machine load starting late at night and finishing the following day, the analysis considers two distinct loads (one ‘half’ for each day). This is not a frequent case as most washing machine loads running at night start after midnight (possibly due to the Economy 7 rate starting at 00:30 GMT). **Figure 5-7** shows an example of load shifting. We can observe the actual load (in blue) in the evening shifted towards the middle of the day (in green), when there is solar electricity generation (light blue line). The shifted consumption (in red) is visible when it differs from the actual one (in black).

Quantifying the potential of washing machine load Shifting

We ran our Best Shifting Algorithm across all participating households over the eight months. Then, computed the percentage of the washing machine consumption that came from the grid which could have

come from the solar PV. We called this percentage the ‘potential improvement’. **Table 5-3** presents the results. These values allow appreciating how much we could have increased the percentage of energy coming from the solar PV in the washing machine consumption. The average potential improvement of all the participating households over eight months is 23.1%. Furthermore, it is worth mentioning that between 11% and 15% of potential improvements were during winter months when the generation is low.

Table 5-3 Average potential and disruption of washing machine load shifting across all participants over 8 months.

	June 13	July	Aug.	Sept.	Oct.	Nov.	Dec.	Jan. 14	Average
Potential Improvement (%)	29.9	32.6	32.4	26.9	22.5	14.5	14.9	11.0	23.1
Potential savings (kwh/month)	2.52	2.48	2.08	1.39	1.51	1.26	0.98	0.69	1.61
Potential savings (£/month)	0.30	0.29	0.25	0.16	0.18	0.15	0.11	0.08	0.19
Time of Shifting (minutes)	182	175	145	136	109	99	99	98	130

The potential savings that could have been achieved through washing machine load shifting in pounds and kilowatt-hour per month are small (**Table 5-3**). The average savings for a month is 1.61kWh (0.19£) for one household (2.28£/year). However, these values have to be related to the washing machine electricity consumption. In fact, the washing machine represents only 1.82% (**Table 5-2**) of the overall electricity consumption. This result stresses the motivation for washing machine load shifting. Do ‘Demand-Shifters’ realise the small benefits of this practice? How do they react to this information? Otherwise, what are the non-monetary motivations of such a practice?

It is interesting to look at the ‘time of shifting’ – the duration in minutes that is required to shift on average in order to get the best time to start the washing machine (**Table 5-3**). This time is absolute, meaning that it could be a shift earlier or later in the day. Considering the actual start time of a load as the householder ‘ideal’ time to run the washing machine, this time of shifting represents the *disruption* implied by the load shifting. The average time of shifting is 2.16 hours (130 minutes) for our participants over the eight months of the study.

5.2.3 SUMMARY

In this section we presented the collection and analysis steps of the Participatory Data Analysis. Our objective was to provide an overview of the multiple electricity flows in the context of domestic micro-generation over different timescales. We emphasised the small consumption of the studied washing machine, representing only 1.8% of the overall consumption. However, our Best Shifting Algorithm showed 23.1% of the load

consumption drawn from the grid could have been powered by the local generation on average across the participants. These observations do not provide enough insights to understand the laundry routines. A lot of contextual information is missing around each washing machine load to understand why it has been run at a specific time.

5.3 DESIGNING AND REFLECTING

Relying on the quantitative analysis, this section presents the core of the Participatory Data Analysis: designing personal infographics to support participants' reflection on their own data and build a better understanding of the context in which each washing machine load has been run.

5.3.1 DATA AND VISUALISATIONS

To support the participants' reflection, we had to help them remember the washing machine loads, specifically the time and the related environmental conditions such as the weather. Furthermore, we had to present them what we observed – percent of green consumption and potential shifting – in a format they could easily and quickly understand with a short face to face explanation as part of an interview.

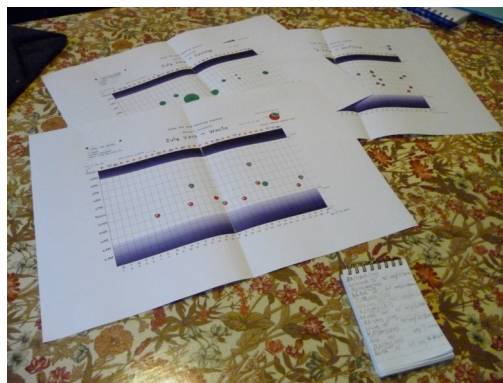


Figure 5-8 Laundry and Washing Machine Study - Participatory Data Analysis in situ (H17wm).

Through our design iterations, we quickly focused on the agenda metaphor, bringing a strong emphasis on the time. Trying different time scales, we selected the month which shows a reasonable numbers of loads in contrast with the week which could only show a limited number of loads at a time. While our initial version was animated with Processing, we chose to present the visualisation on static A3 hard copies. The paper version is more effective and tangible, focusing on the information while avoiding diverting the participant into the evaluation of a potential ambient display. In fact, these visualisations were not intended to be shown on an ambient display, but rather to support a 1-time in-depth discussion of laundry routines in the context of

local solar generation. The hard copy also gives the opportunity to write notes on the charts, allowing to ‘edit’ the visualisations during the discussion with the participants.

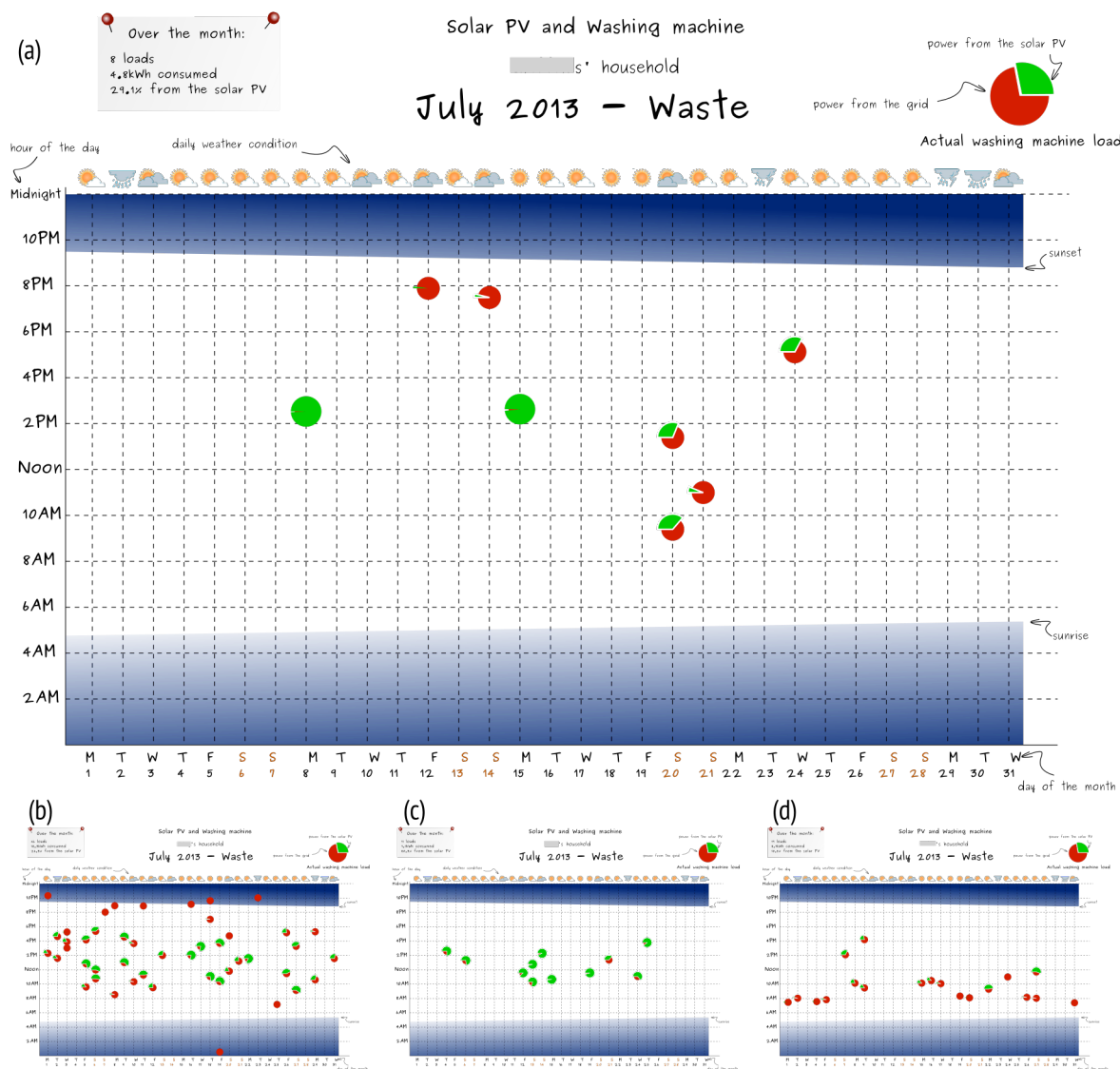


Figure 5-9 Washing machine load waste over July 2013. a: H12_{WM}, b: H16_{WM}, c: H14_{WM}, d: H4_{WM}

Figure 5-8 shows an example of interview setting at H17_{WM}'s place. Each washing machine load was indicated as a distinct event in the monthly agenda, and was represented as a multi-coloured dot. Each of Figure 5-9, Figure 5-10 and Figure 5-11 presents examples of the visualisations for the same four participating households in July 2013. In these Figures the y-axis indicates which time the wash was started, from the morning at the bottom to the evening at the top. The lower x-axis indicates the day of the week and date for the wash. The sunrise and sunset times were visualised through dark blue bands, thus leaving a clear window of sunshine hours in the middle, shown to be gradually changing as the month progresses. The actual weather for each day, in the form of a 'sunshine' or 'cloud' symbol etc., was displayed at the top x-axis providing

contextual environment for each day. We manually designed the layout of the visualisations with the vector editor Inkscape and our Java program drew the data on top of it.

The first visualisation (**Figure 5-9**) uses a pie chart model to materialise the start of each load, showing for each of them how much electricity was coming from the solar PV and how much electricity was coming from the grid. This visualisation thus gave a quick overview of the ‘green-ness’ of the household's loads over the month and helped open the discussion. The bottom of the pie chart represents the actual start of the load. For example, on July 20th (Saturday), towards the middle of the visualisation, H12_{WM} (**Figure 5-9a**) did two loads of washing, one around 9A.M. in the morning and one just after noon, both taking about a third of their power from the solar PV.

The participants were all familiar with the concept of importing and exporting electricity and this first visualisation was mainly designed to draw their attention to potential opportunities to increase their self-consumption. We deliberately gave this the title 'Waste' – to be provocative (even though there is no actual waste) and to make the point that participants could have consumed more electricity coming from solar energy and thus reduced their electricity import from the grid. The objective would be to have a full green circle, which means that the washing machine load had been entirely powered by the solar PV. A summary board on the top left corner provides the number of washing machine loads ran over the month, the amount of energy it required and the percentage of it that has been covered by the solar PV. Looking at **Figure 5-9** we can quickly notice the wide variation in number of loads. H14_{WM} (c, middle bottom) is one of the more diligent participants with 80.3% of the energy consumption by the washing machine coming out of the solar PV. We can observe a regular pattern of loads in the morning for H4_{WM} (d, bottom right) while there are simply too many loads for H16_{WM} (b, bottom left) to be all run during the day.

We designed the second visualisation to show participants when would have been the ‘greenest’ time to start the washing machine and how much delay it would have implied. **Figure 5-10** shows an example of this shifting visualisation with the actual loads as red circles and the best time for this load in green circles. For example, towards the end of the month, on July 24th, H12 (**Figure 5-10a**) carried out a washing load late in the afternoon (red circle between 4 and 6P.M.). On the same day, the green circle at noon indicates that noon would have been a better time for this load, given the specific weather for that day. Using this chart, we phrased the questions in terms of ‘*Would it have been possible to...*’ with further questioning to find out the

context and the constraints that made this happen: was it because they did not think about it? Or was there a type of emergency that drove to these ‘bad’ loads? On this visualisation the summary board (top left corner of the visualisation) indicates the overall improvement that all these changes would have generated, the time of shifting it would have required and the number of ‘ideal’ loads which had been ran at the best time.

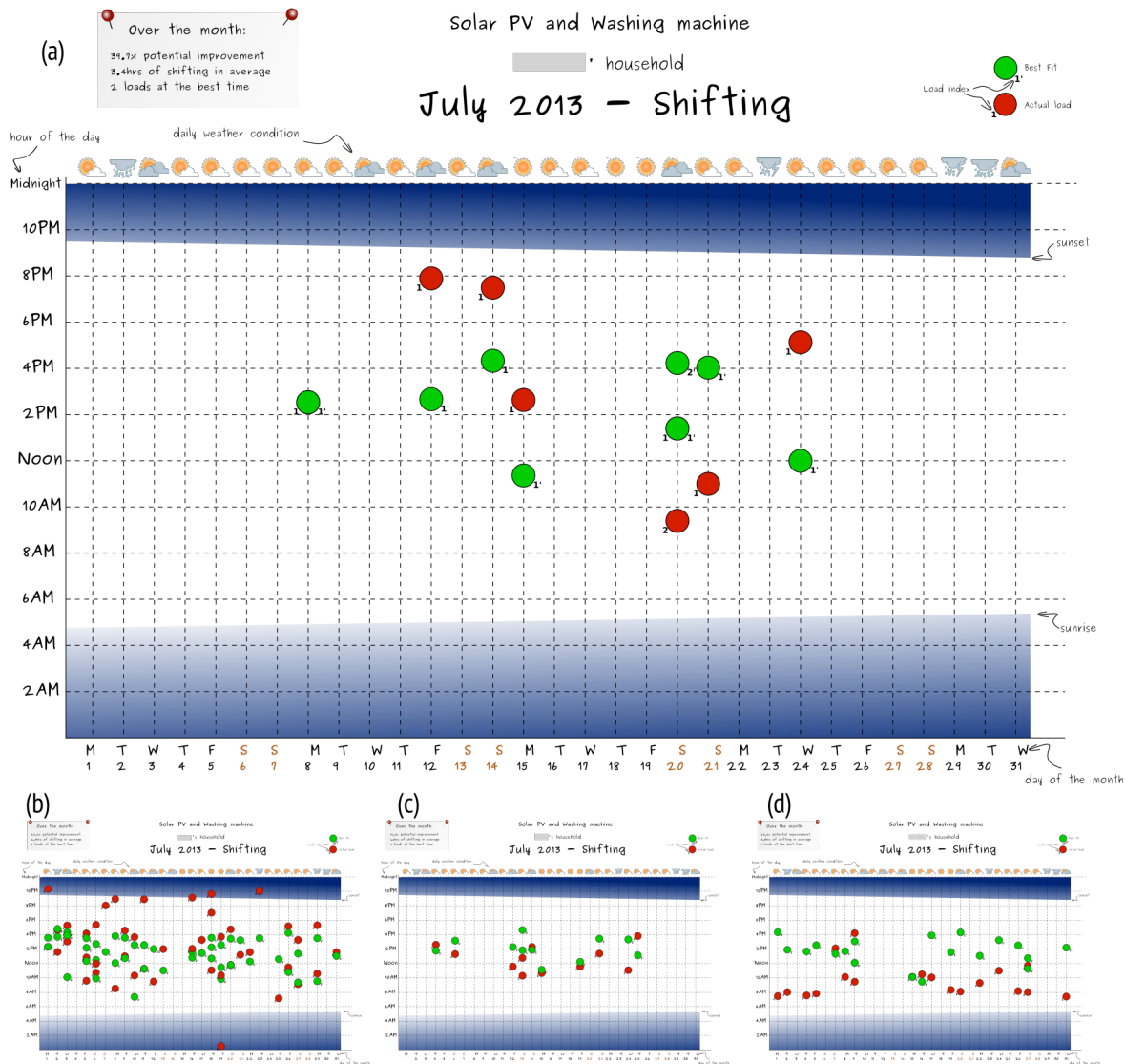


Figure 5-10 Washing machine load shifting over July 2013. a: H12_{WM}, b: H16_{WM}, c: H14_{WM}, d: H4_{WM}

The final visualisation is about savings: ‘How much will it save to shift a load’. In **Figure 5-11** the size of each circle represents the amount of savings; the position represents the best time to run the load. Many loads are invisible as the savings would be too small to represent in the diagram. Note that shifting washing machine loads is often a matter of saving just a few pennies per month, as highlighted in the previous section. However, this visualisation was interesting because it allowed us to observe how participants, already aware of their own electricity, react to such tiny savings. How much do they care about such savings? How much effort are they

living-room table. We were also able to show further visualisations of data for other months on an electronic tablet which we could turn to if it seemed relevant in the context of the conversation. After several interviews it became clear that the summer was too far back in time from the period of interview (end of November) for participants to remember specific events. We were then able to generate the same visualisation for the month of November and show these on the electronic tablet.

5.4 FINDINGS

We extracted three main themes from our thematic data analysis: shifting and the context around shifting; decision making; and the issue of convenience. In this section we introduce general insights of the interviews then we go through these three main themes.

5.4.1 INSIGHTS OF INTERVIEWS AND VISUALISATIONS

There were some interesting trends we noted in the data. For example, households differed hugely in the number of washes they did per week, from less than 1 to more than 8 per week. It was not necessarily the case that the biggest households had the highest number of washes. Also, not many wash loads (only 315 out of a total of 1960 loads observed) were carried out during the dark hours when there is no generation.

Many participants expressed delight and surprise to see their own data presented through the visualisations. Many of them remarked that it was quite different from the views they usually see on the web portal, showing either real-time electricity data or historical trends. In H3_{WM}, the husband reflects on the different types of insight gained from the visualisation ‘Waste’.

H3_{WM} (husband): ‘the portal actually gives us a summary of how much energy we use for the washing machine [...] This one now tells us that by adjusting the time, by shifting it (it makes no difference to us) so we could actually do that. But it’s knowing when that best time is ...’

Many participants were also keen to better understand their own context at the time of the washing loads being visualised, saying: ‘can I just get my diary’ (H2_{WM}, wife). With the help of their dairies they would bring up details, such as a busy week at work, school holiday, or visitors staying in the house which would further explain the pattern of washing loads they were looking at. In H17_{WM}, the wife had made specific notes about her washing loads herself, and was eager to compare these with the data presented in the graph – See **Figure 5-8**.

5.4.2 SHIFTING IN CONTEXT

In our questioning we wanted to know whether participants could imagine doing even more shifting than they were doing already. That is, was there room for improvement? The few participants, who were already doing their washing at a good time in the day, mentioned that seeing the visualisation came as confirmation of how well they were doing. They did not think it would be possible to improve their behaviour even further, but the insight confirmed that they were doing well and made them feel good. Others mentioned how the shifting visualisation (**Figure 5-10**) could be interpreted as a target that they should aim to achieve. Some participants mentioned explicitly that they expected to be able to reduce the time between the actual start time and the best start time with the support of an automatic system.

H16_{WM} (wife): ‘haha! so now I think I hope that the next time we see a chart like this that maybe there won’t be so much green on it because the weather is different. No, but I hope we will be hitting the green marks’

The main objective of the ‘shifting’ visualisation was to understand if the participants would have been able to shift their actual washing machine load to the ‘best time’. Many participants remarked that indeed a large number of loads were shiftable, and that if there were an automatic system to help them achieve that they would welcome it:

H16_{WM} (wife): ‘oh absolutely, if the machine is going to switch on then I can just pop it in the machine at 8 o’clock and it would run automatically at noon. So I come home and it’s done’

H9_{WM} (wife): ‘I think that’s certainly feasible to do, let say a load a day, and just fix it at the best time each day. That’s not a problem’

With respect to being able to find this ‘best time’ manually, for many people this appears difficult to achieve. This was even the case for those who spend a lot of time at home, and who consider themselves expert at catching the sunny time-slots. This became evident around the ‘shifting’ visualisation by looking at the distance between the actual and the best start time which often showed a difference of 1 hour. Clearly some of the participants were disappointed, as they were expecting to see some one hundred per cent green loads. It is interesting to observe this contradiction: the ‘green’ participants feel reassured by the ‘waste’ visualisations, as it confirms they are on the right track – but the visualisations showing details of better starting times shows that they have still quite some scope for improvement.

In and Out

In the discussions around shifting, participants brought up a range of issues that stood in the way of them achieving the maximum self-consumption. One major recurring theme was work, and being away from home.

H7_{WM} (man): ‘Me, I get up at 6 o’clock or 5:30. I’m out the door at about 6 and I’m back at 10 and I’m working all day. I don’t really have much time to do anything, even at work. Let alone check this tab and the other. It’s not that I don’t think it’s important but for me, me as a user...’

People discuss how they have different ways to cope with how they do their laundry: starting the washing machine or make sure it is finished by the time they leave the house, set up the delay on the washing machine to start later, or group the loads on a rest day or weekend.

Certain activities, such as school and sport, are also mentioned as two major obstacles to the washing machine load shifting. Many of the families with school age children mentioned it was imperative to wash the school uniforms over the weekend, to get them ready for Monday morning. They felt this was a process that could not be started before Friday evening, and for them the window of time to do the washing, drying and ironing did not offer a lot of flexibility.

H8_{WM} (husband): ‘he’s at school (son), obviously. So we need to make sure about the end of the week that everything gets washed over the weekend, so it has a chance to dry. We don’t use the tumble-dryer - we dry naturally - so we try get it done. Although we would try using the washing machine during the day when we can, there are times when we run it at night or during the evening to make sure the wash loads are done.’

Gym, tennis or other sports also pose various forms of constraints. These activities are often in the evening and a few participants mentioned that they want to wash their clothes right away when they come back.

H8_{WM} (husband): ‘when my son comes back from tennis, all his tennis clothes go straight into the washing machine hmm...’

H1_{WM} (woman): ‘I went to the gym, that was in the afternoon, I came back and washed the clothes [...] I don’t like having smelly gym clothes lying around’

In H1_{WM}, the woman considers herself a very keen and green demand-shifter, with strict self-imposed rules to try and maximise the use of generated electricity. However, all her normal routines fly out of window when it comes to gym clothes – those have to be washed straight away.

A series of life events are often the source of a less controllable period. Families with younger children often talked of unpredictable emergencies such as a child being sick in their bed which then can lead to a different pattern of washing.

Older children who have left home but come back for longer periods insert a large amount of randomness in two different ways: first, they keep the parent busy and increase the number of dishwasher loads for example, or on a longer period those of the washing machine. Second, if they are using the washing machine they are not fully aware or concerned about using electricity from the solar panels.

H6_{WM} (husband): (talking about his daughter) ‘suddenly -oh I’m going back to college tomorrow – (gestures) – and then she puts everything in the washing machine...’

H5_{WM} (wife): ‘There have been couple of incidents when my son is here and I say (son’s name), can you put it in the machine at a sunny time of day and he hasn’t...! He’d turned it on at 2 o’clock in the afternoon, which is not good for our solar!’

Laundry

The laundry activity itself also has internal constraints related to the Demand-Shifting process. A large number of participants use the term ‘*wanting to clear the washing*’ or ‘*catching up with the washing*’ expressing a way of doing their washing all at once, usually at the end of the week and over the weekend.

The particular design of the washing machine used by all participants also plays a significant role in the process of doing the laundry. First, the large drum of this washing machine allows the condensing of two loads into one. This reduces the number of washing loads that need to be done. Second, most of the program cycles take between two and three hours to run, as a result of the machine being designed to avoid large sharp peaks in its consumption of electricity. However, the length of the cycles reduces the flexibility of use. Some participants don’t want to leave wet clothes sitting in the machine for a long time after the load completes, others are less concerned. Whether or not the user wants to be at home when the washing machine has just finished has an impact on the laundry time flexibility.

The method of drying is a direct constraint on the washing routine. Most participants do not use a tumble-dryer because they are conscious that it is a high energy consumer. For the participants who do use a tumble-dryer, they do not use it systematically.

H16_{WM} (wife): ‘we don’t use it through the summer, we use it sparingly in the winter’

For the participants who dry their clothes ‘naturally’, there is a major constraint of time.

H8_{WM} (man): ‘we do have constraints about when we need the washing dry by, because we don’t have a tumble-dryer - we don’t - we just dry the clothes’

Participants talk about having to find a balance between using the sun as electricity or as direct energy for drying. For many it is about running the washing machine early in the day in order to be also able to use the sun for drying the clothes naturally or for running the tumble-dryer. This model tends to be less constrained over the winter when drying clothes outside is not an option any more.

H12_{WM} (husband): ‘Now in winter it’s not much an issue because I don’t dry outside so it doesn’t really make much difference. So to be honest I can wash it at any time and the best time, as long as I’m around to take the washing out’

5.4.3 DECISION MAKING PROCESSES

One theme that appears as crucial in the context of laundry and electricity Demand-Shifting is the decision process. How do people decide? How do they make the choice to turn on the washing machine at a specific time? Is that decision really conscious? What are the motivations and parameters that play a role in this process? In most cases the decision relies on interpretation of information but also on expectations.

Source of Information

Most householders with solar PV on their roof relate their own electricity generation to the weather. Many of the participants use their smartphones or electronic tablets to check the weather forecast before starting a wash. Although this information is used either for the current and the following days, it is mostly used to determine whether the following days will be better (sunnier) or not. In other words, is it better to do the washing today or is it better to wait a couple of days? This 'shifting' decision comes into play when there are no specific constraints or emergencies for the current day.

H12_{WM} (husband): 'I was looking at the weather. I go into the tablet and look at the weather, think OK, but that's a conscious decision by me to kind of do that and think ahead.'

Some of the participants, particularly older participants, do not find the weather forecast reliable enough generally. Even though most of them check the weather forecast – on their smartphones, tablets or TVs – they use what one participant call the 'human element' while other participants talk about 'looking out the window'.

H10_{WM} (husband): 'I don't find that the weather forecast can be reliable enough, certainly this time of the year when it does vary'

Technical Considerations

Participants also base their decisions on their expectations about the generation of their solar PV. Technical considerations can drive people to expect more generation in the morning because of the solar PV position on the roof for example. However, these expectations are sometimes wrong.

H5_{WM} (husband): 'we've got more panels going south west than we have south east so we would get more generation earlier on'

Some people were really surprised when being shown the washing machine loads visualisation because they were expecting a different best time. One participant was not expecting such strong impact of the weather, thinking that running the washing machine at midday was obviously the best time.

H5_{WM} (husband): 'yeah we put it on at half ten and you said the best fit was 2 o'clock, I would assume that half ten would have been a better fit than 2 o'clock'.

5.4.4 MOTIVATIONS AND CONVENIENCE

Although the weather and other sources of information are used for a specific day or load, there are some more high-level drivers such as saving money and taking care of the environment. In the UK those with both environmental impact and monetary savings goals find the situation more complicated, especially in winter. They need to decide between running more appliances during the night (when electricity is cheaper and a higher percentage comes from wind) or during the few sunny hours (when they can at least partly use local micro-generation).

Although most of the participants are convinced by the benefits of electricity self-consumption some were not convinced, even though they were still very much motivated by environmental concerns. For them exporting to the grid is equally about contributing to a greener energy system.

H16_{WM} (wife): '... but we import it again! So we probably export all this energy and then we buy it back, don't we? To run something else and that's surely not right.'

H17_{WM} (wife): '... as far as I'm concerned, as environmentalists, we are kind of happy contributing anyhow because it's not actually going to waste. It's being caught and used somewhere else. So I can't see the advantage of using energy directly compared to when it's going out of the house'

Money savings are generally strong motivations to drive the behaviour. However, a balance has to be found between convenience and money savings. In fact, washing machines in general are not huge electricity users, especially the A+++ energy rated washing machine we used for the study. On top of that, most of our participants were already trying to shift their load manually, which makes the potential savings even smaller. The average savings that our participants could have achieved over a summer month, i.e. if they had run all their actual loads at the best time, would have been about 70p per month.

H6_{WM} (husband): 'you've got two things going in parallel: the first thing is your life, you know. Certain things have to be done and start anyway so you can't concentrate 100% on making sure that this is absolutely right; but in parallel with that you're also learning, this optimal period in the middle of the day, even if the sunshine is at 6:30 in the morning it's obviously not generating enough to do much with, hmm, so that is a sort of learning curve.'

It was interesting to observe the reaction of participants looking at these monthly savings. Three of them thought instinctively of coffee: '3 pounds a year I mean! I buy a cup of coffee for that!' (H14_{WM}'s wife). Participants think about the effort that is involved in shifting and how this balances with their comfort and convenience.

Although they were mostly aware that they were not saving lot of money from the washing machine load shifting, they were all surprised to learn how tiny the benefits were.

5.4.5 APPLIANCES

Extending the discussion from the washing machine to other appliances in the house, we build a map of the potential shiftable and non-shiftable appliances, and we emphasize the interaction between appliances.

Shiftable/Non-Shiftable Appliances

The washing machine, dishwasher and dryer are the most common appliances that participants mentioned as shiftable. Although it has to be reminded this topic was discussed in the context of interactive Demand-Shifting. However, there are only tiny savings to be made and participants were interested to discuss how they could approach Demand-Shifting with different appliances that they know as more important in terms of their consumption.

The hot water heater and space heating were mentioned as good shiftable devices. Participants described how to make Demand-Shifting much more automatic for these kinds of appliances. When automation would be expensive, e.g. replacing the device, participants suggested semi-automatic solutions. For example, the wife in H11 suggested that she would be happy to receive a prompt by text message suggesting a good time to start the immersion heater (for the hot water cylinder). She felt she needed more information to know when it would be valuable to turn on the electric hot water instead of consuming gas to heat the water. All the participants but one had gas space heating, the most important part of the electricity bill. Although the solar PV cannot power the gas heating system, several participants describe situations where they have or they could have implemented an electric heating system in the living room to complement the gas consumption when they have spare electricity generation.

Other heavy and shiftable appliances are less common and participants discussed methods they have developed to manage them. For example, the husband in H11_{WM} is the only one with a heat pump. In the summer, the device runs only to heat the water. He has set up a timer to turn it on only between 12A.M. and 2P.M. so that the pump gets powered through the solar panels. Other participants operate similar processes with appliances such a hot tub or their bread maker.

Participants also mentioned a list a non-shiftable devices including media devices and specifically the television. The oven is a heavy load and participants are well aware of the fact that it is a heavy consuming

appliance. However, although they do not tend to change their dinner time, we did observe subtle changes in routines and habits around the usage of cooking appliances. For example, they were able to group the cooking of several dishes together, or aim to do most of their cooking during the day time, in advance, and for several days. They also mentioned avoiding the running of other major appliances at the same time as doing their cooking.

Interaction between Appliances

Most of the participants mentioned that there are issues to do with the interaction between appliances. As mentioned above, activities such as cooking (using the oven), cleaning (vacuuming, ironing) or more exotic devices such as a heat pump or hot tub have an effect on whether or not to run other appliances. Numerous participants mentioned they had developed a ‘rule’ – which was ‘*do not run at the same time*’.

H11_{WM} (husband): ‘I have the hot water on between 1 and 3 o’clock so we try not to run anything else between 1 and 3 o’clock because then we maximise. We never put the washing machine on around 2 o’clock I think’

Participants also mentioned that it is difficult to actually carry out this rule manually – to shift between the various appliances in the house. It can also lead to tension between members:

H6_{WM} (husband): ‘I say to her, well the tumble-dryer is using a lot more energy so sometimes she says ok the sun is shining brightly, use the tumble-dryer when that’s finished to use the washing machine.’

5.5 DISCUSSION: UNDERSTANDING LAUNDRY ROUTINES

The decision process around Demand-Shifting is time-consuming and requires a combination of indicators ranging from the weather forecast to the ‘human element’. This decision process is described as difficult for some participants lacking information or impossible for some others because they spend most of their time away. Similar to the conclusion of Banerjee in their study of an off-grid house (Banerjee, Rollins, & Moran, 2011), we highlight that participants want to anticipate: they base their decisions on real-time or forecast parameters rather than energy feedback.

Previous research has highlighted a few categorisations to indicate whether appliances are considered shiftable or not (Haghighi & Krishnaswamy, 2011; Zhu, Tang, Lambotharan, Chin, & Fan, 2012). In these categorisations the emphasis is on the appliance itself and its functionality. However, our study has shown that there is wide variety in the ways different households engage with Demand-Shifting for one particular appliance – the washing machine. The washing machine is generally considered an appliance that is capable of being shifted with relative ease – but our research showed that for residents to properly engage with Demand-

Shifting of the laundry is a considerable effort, and one that does not bear a huge economic benefit. The property of being shiftable does not so much depend on the appliance, but rather on the household, the residents and the specific situation. Furthermore, the specific design of the washing machine – its drum size, the length of its program cycles has a large effect on making it more or less shiftable. In particular, if considered in the context of residential electricity generation, a longer program cycle makes the appliance less flexible in terms of shifting, whereas shorter cycles make for easier scheduling. Furthermore, an appliance that is generally considered not to be shiftable, the cooker was discussed and we highlighted subtle ways for household members to change their routines around such appliances thus making the appliance more shiftable.

However, most of the participants clearly state that they are not able to run their washing machine at a better time without support. In emergency situations, there is needs for digital technologies to select the least bad solution that allows users to satisfy a short-term need. Apart from emergencies and being away, the biggest constraint to shifting appliance loads is related to the other appliances. Demand-Shifting is also about how to synchronise local electricity generation and multiple electricity consumption constraints. We highlight a need for digital tools to support this through a communication between appliances and user interfaces that distil information at the right time and adapt the information to support the user in the decision process.

Finally, depending on the effort that the participants spend on increasing their self-consumption, we observed that the visualisations had different effects. While some visualisations could be used to help formulate targets, others act more as an acknowledgement – but the three visualisations together provided a vehicle for in-depth reflections on behaviour and opportunities for householders to learn from this. We suggest that this information should be designed as a function of the motivation intensity of the participant. This study goes beyond Kobus' work (Kobus, Mugge, & Schoormans, 2013), highlighting the context and decision making around shiftable appliances and the strong relation between the different appliances in the house. It also confirms from the user point of view that there are shiftable and not-shiftable appliances. However, most of them reduce the flexibility of each other's loads.

5.6 REFLECTION ON THE PDA METHOD

In-the-wild studies in the residential environment are challenging. This is even more difficult when it is about analysing data from multiple electricity meters to compute detailed mappings of washing machine usage. However, our methodology – combining data analysis and in-home interviews – to discuss how to improve

the self-consumption of a highly contextual activity such as laundry routines, revealed new insights and allowed participants to reflect and learn about their own behaviour.

Through the PDA, we used the opportunity of having access to quantitative and qualitative data and being able to interact with the participants as a strength to build a better understanding of the relationship between local generation and appliance usage. We helped participants reflecting on their laundry routines, how well they were at shifting this activity and how this could have been improved.

The major benefit of this method is the ability to double check our interpretation of the data with the participants and grasp deeper insights. There was a significant gap between our interpretation of the collected electricity data and how people actually reflect on their own data. For instance, some participants were performing very well without much effort as the ‘best’ times to run their washing machine seemed to fit with their daily routines. In contrast, some participants were engaging really well in manual Demand-Shifting and their electricity data did not reflect that.

The personal infographics helped us in engaging the participants during the interviews. Sometimes they were leading the interview, jumping from washing machine events to related topics. This highlights the importance of the initial infographic design to lead the discussion towards what we are looking for. In addition, it is necessary to master the electricity data of each participant in advance and to establish a list of questions about data points we do not understand. In our case most of these questions were answered implicitly by the participants, but it helped opening or concluding the discussion in some interviews.

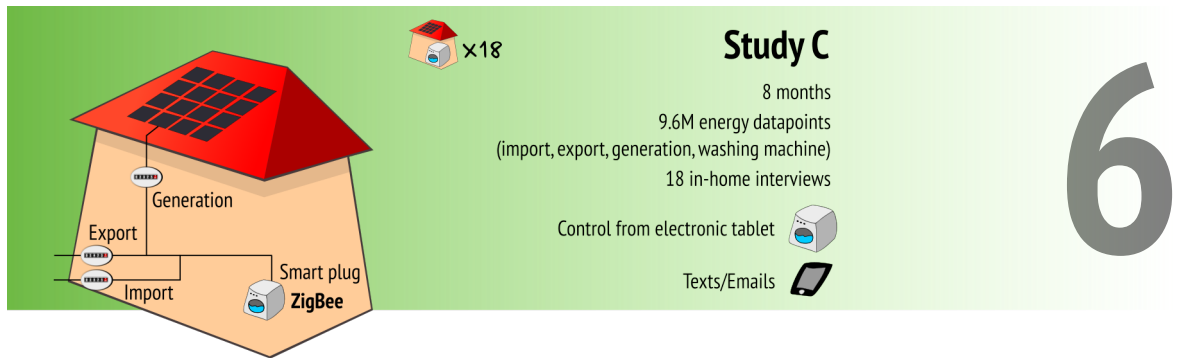
We conducted most of the interviews in participant’s homes, at a time of their convenience including evenings and weekends. Behind this process, our intuition was to create the best conditions to get participants comfortable talking about their personal daily routines. Actually, it provided much more beneficial than we expected. At home, participants were in the context of their daily routines. They were able to describe situations by leading us through their house. They had access to their diaries, calendars displayed in the kitchen or notepads where they were manually logging solar generation. These elements created much richer stories and generated connections with anecdote and other events. It was also an effective way to remind them of the context of each washing machine load as these events are not really those they normally remember.

In most cases, we collected better insights when several members of the households participated in the interviews. Participants were reacting to each other's comments and explanations. As in most participating household the laundry was managed by one person, it was also a good way to capture insights from both sides: laundry 'managers' and 'others'. Finally, it is difficult to find the right time to conduct the PDA. We designed this method in the middle of the study process, while realising we were missing significant insights by relying only on quantitative data and initial qualitative data. Retrospectively, it could have been better to conduct the PDA earlier in the study process because it provided information that could have been integrated into the intervention phase that we present in the next chapter. However, by doing so our knowledge about the context would have been smaller, impacting the way we designed the infographics.

5.7 CHAPTER SUMMARY: THE COMPLEXITY OF DEMAND-SHIFTING

To understand the relationship between local solar electricity generation and appliance usage, we looked at the washing machine consumption of 18 participating households over 8 months. We designed and implemented the PDA to enriched our interpretation with participant's analyses. We quantified the potential of shifting the time of running the washing machine. It would significantly increase its percentage of electricity consumption coming from the local solar PV, while the monetary savings from the perspective of the overall system would be negligible. This relates to the low consumption of washing machines.

We highlighted the complexity of the environment and decision processes around Demand-Shifting and discussed the potential shiftable devices, noting that interaction and synchronisation between appliances is a major obstacle to interactive Demand-Shifting and has to be part of further explorations. While we brought out the engagement and the willingness to engage in Demand-Shifting, this process is time-consuming and requires the consideration of many parameters from energy and weather predictions to contextual information. Users have access to increasing but still limited information and shifting happens manually. This highlights the challenge of reducing this effort by supporting these practices without reducing the engagement emerging in this context. This understanding of Demand-Shifting builds the foundation for further investigations to explore the potential of digital tools to address the highlighted challenges: which systems can support users by balancing convenience with the complex decision processes needed to deal with changing day to day constraints and priorities in electricity needs? This is the focus of the last study around the washing machine, presented in the next chapter.



Supporting Demand-Shifting Behaviours

In-the-wild Interventions around the Washing Machine

'I can't change the direction of the wind, but I can adjust my sails to always reach my destination.'

JIMMY DEAN, ON 'GOOD MORNING AMERICA', ABC

Digital technologies can potentially play a role in helping people become more effective 'demand shifters'. To improve our understanding of the technical and social issues and – most importantly – their interrelationship, we conducted an in-the-wild user study. We decided to explore a range of technology interventions – rather than focusing on evaluating one specific technology design. Specifically, we decided to explore four interventions along a temporal dimension.

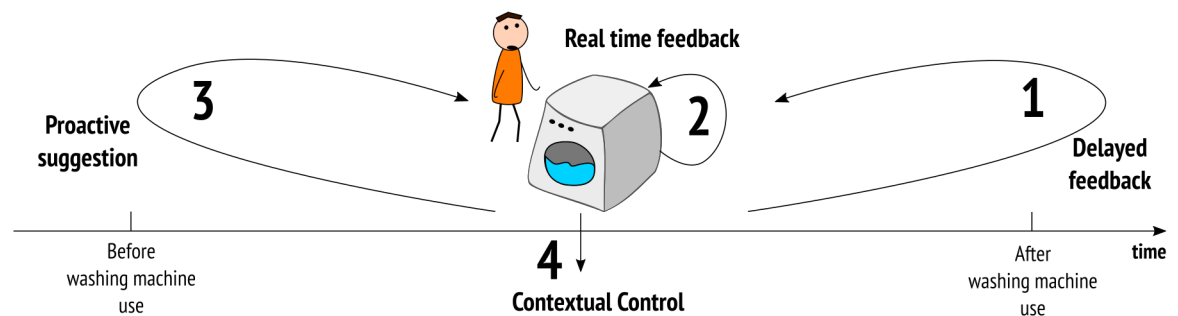


Figure 6-1 Interventions through the washing process.

Figure 6-1 illustrates the design space of these four interventions. The horizontal axis indicates time, with events taking place before the use of the washing machine shown to the left and events taking place after the use of the washing machine to the right.

1. The first intervention, which we refer to as *delayed feedback*, entails the use of email to inform members of a household how well their laundry activity aligned with energy generation *several hours after* they used the washing machine (typically at the end of the day).

2. The second intervention, which we refer to as *real-time feedback*, entails the use of text messages to inform members of the household how well their laundry activity aligned with electricity generation *immediately after* they used the washing machine (typically within a minute after the washing machine turned itself off).
3. The third intervention, which we refer to as *proactive suggestion*, uses text messages to inform members of a household at the beginning of each day about the best time to do the laundry during that day – i.e. *several hours before* the use of the washing machine. ‘Best time’ in this context refers to the start time that would maximise the consumption of self-generated energy (and thus minimise the energy export to the grid).
4. Finally, the fourth intervention, which we refer to as *contextual control*, entails the use of an interactive display attached to the washing machine to inform members of a household about the best time to do the laundry *and* to enable them to set the machine to *automatic start*, a new washing machine control mode we designed to start the machine automatically at the best time. As before, ‘best time’ refers to the start time that would maximise the consumption of self-generated electricity.

6.1 IN-THE-WILD INTERVENTIONS

In this section we present an overview of the system we implemented to deploy the interventions, the participants and the evaluation.

6.1.1 IMPLEMENTATION

The first intervention relies on accurate analysis of energy consumption and generation during that day in order to compute shifting benefits. The third and fourth interventions rely on a predictive model of household specific electricity consumption, generation, import from grid, export to grid, local weather and washing machine use based on historical data collected over several months from each household.

We relied on existing works from the literature, detailed in Chapter 2 (p. 41), to build predictions for the overall electricity consumption and the local solar electricity generation. We designed two generation predictions. The first is based on the next 36-hour forecast of cloud cover and the past generation over the last 20 days. The outcome G'_i of the prediction is the amount of expected energy generation over a 15-minute time-slot i . The system looks for the maximum generation G_i over the last 20 days during this specific 15-minute time-slot i and applies the cloud cover CC'_i prediction as follows:

$$G'_i = \max(G_i) * CC'_i \quad (6-1)$$

The second prediction relies on the last 15-minute of generation. The system selects the prediction which performed the better during the last time-slot. This combination of techniques allows us getting 15% of

accuracy during the first couple of hours and then 20% (Normalised Root Mean Square Error). We also designed our overall consumption prediction based on the last 20 days of consumption. We inspired this solution from the occupancy algorithm from Scott and colleagues (Scott, et al., 2011).

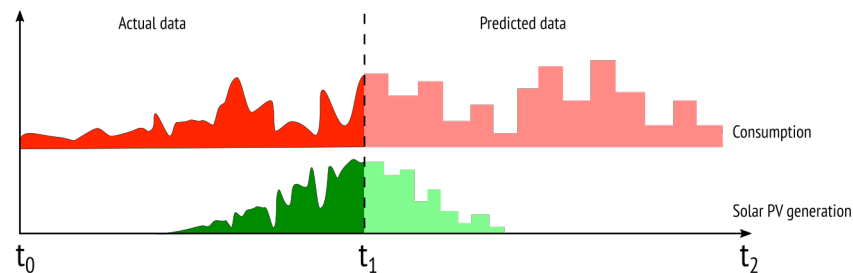


Figure 6-2 Energy over the current day – Partly actual/Partly predicted data.

As shown in **Figure 6-2**, at t_1 the algorithm computes the predictions of consumption and generation and combines them with actual data collected till t_2 . The result provides a complete energy profile covering any time required for real-time feedback, proactive suggestions and contextual control. In contrast, the typical delayed feedback is generated in the following days, when data have already been collected for the full day.

6.1.2 PARTICIPANTS AND SCHEDULE OF INTERVENTION

We conducted this study with the 18 participating households presented in the Section 5.2.1 (p.82) over a period of eight months. We divided the 18 households into two groups with 6 and 12 participants respectively. We used the Group 1 as test group before deploying Interventions 1 and 2 on Group 2. Due to time pressure, Intervention 3 was not done with Group 2 and Intervention 4 was deployed on both groups at the same time. **Figure 6-3** shows the different stages of the deployment, divided in two groups of participants.

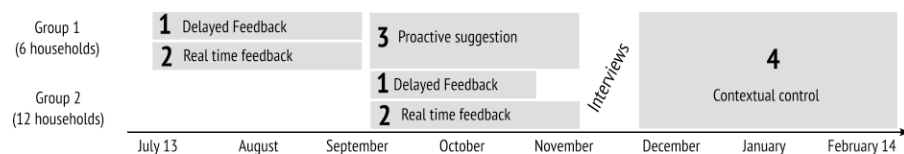


Figure 6-3 Timeline of interventions.

6.1.3 USER EVALUATION

To evaluate our designs, we collected data through multiple ways. We took the opportunity of conducting interviews for the PDA – study B presented in Chapter 5 – to collect feedback on interventions 1, 2 and 3. During these visits to participants' homes, we also set up the fourth intervention and collected initial impressions. In collaboration with E.ON, we also conducted focus groups with the participants during two sessions (half of participants each time) that took place in meeting rooms away from homes. During these

sessions we asked them for their feedback about the interventions and reflections on their use within their domestic setting. We collected informal feedback during our technical visits and multiple email exchanges. Finally, we used a questionnaire to collect final impressions.

6.2 DELAYED FEEDBACK

We started with the most common approach to eco-feedback: providing information to the householders about what happened in the context of their local generation.

6.2.1 DESIGN OF FEEDBACK VIA EMAIL

For the first intervention, we sent emails to the participants every three days with two sections in each email, as shown in **Figure 6-4**. The lower section showed graphs of historical energy generation over the last five days. Icons of washing machines indicated each load with its duration (length of the ribbon under the icon). This graph aimed to relate the local generation with the specific event of consumption, i.e. washing machine loads.

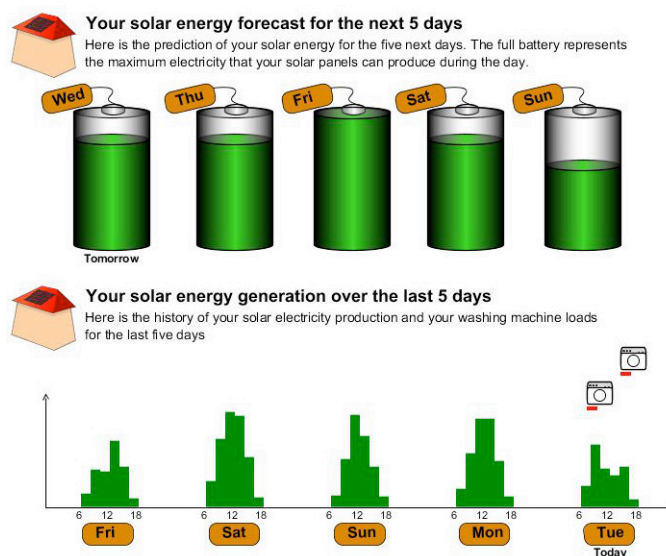


Figure 6-4 Intervention 1: delayed feedback by email. Example of email sent to H9.

The upper section of the email displayed five battery icons representing the amount of energy predicted for each of the five following days. The prediction was based on the daily cloud cover forecast and was intended to inform the user about the potential of their energy generation for the coming days. Five days was chosen as the maximum semi-reliable forecast period for this part of the UK. Even though we included energy predictions, the emphasis of this intervention, as highlighted to participants, was on showing historical data.

6.2.2 FINDINGS: DECONTEXTUALIZED INFORMATION

This intervention did not result in any feedback from the participants. The key reasons were that participants rarely checked email. Many had found that they either received too many emails and therefore ignored these while others checked their email too infrequently for the information to be relevant. The historical information seems to have been too far removed in time, or in place (with a few households only receiving emails through their computer in a separate study upstairs) from the washing loads to have motivated any change in behaviour or comments. Just one participant remarked that he was sorry the emails stopped, as he had found the predicted energy generation information useful for planning purposes.

6.3 REAL-TIME FEEDBACK

To get into a more interactive intervention, we aimed to reduce the time frame between the energy event and the eco-feedback. Thus, we intervened in reaction to the end of the washing machine loads.

6.3.1 DESIGN OF TEXT MESSAGE FEEDBACK

The second intervention involved SMS text messages to participants' mobile phones. The users received a text message after each washing machine load. These text messages contained information about how much of the energy that was used for the washing had come from local generation (in percent), when would have been the best time to start the washing machine and how much local energy they could have used (in percent). **Figure 6-5** shows some example messages. The aim of this intervention was to increase energy awareness relating to local solar PV generation and the potential for local use by a specific appliance (termed 'green consumption'). We wanted to understand how participants reacted to timely energy feedback by text messages and whether or not they made use of these texts.

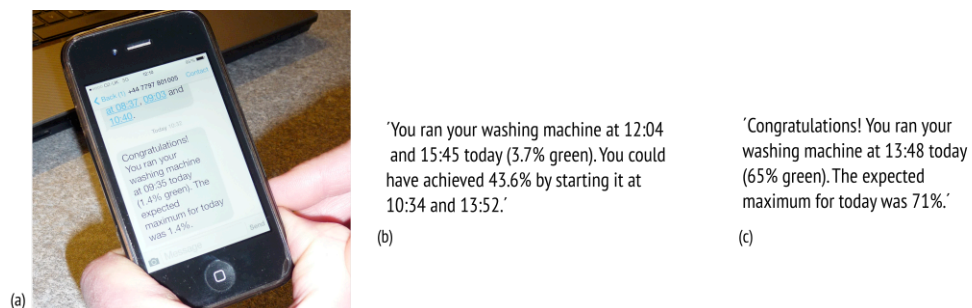


Figure 6-5 Intervention 2: Reactive feedback. a: text message received on H6's smartphone; b: an example of text message suggesting improvement; c: an example of text message which congratulates the participant.

We congratulated the user each time the actual 'green consumption' was at least 90% of the best green consumption achievable. This measure allows the advice to be independent of seasonal variations: if the

weather for the current day is bad, then the greenest consumption achievable is low and users can still be congratulated when they use a large part of this tiny solar PV generation. We fixed the threshold at 90% after trying several values over the first month. This value offers a balance of ‘congrats’ messages and other messages.

These text messages were sent over five months (583 texts), initially to 6 households and later to all 18 households. Our aim was to send the text message as soon as the washing machine was finished so that the message was timely. However, it appears that, due to a technical limitation, we were getting the data about an hour late so the users often received the text about an hour after the end of the load.

We allowed and encouraged participants to reply to the messages, but only a small number chose to do this: we received a total of 5 text messages from 2 of the 18 participating households ($H2_{WM}$ and $H11_{WM}$). Both indicated that participants believed there was an error in the text they had just received.

6.3.2 FINDINGS: IT IS TOO LATE

Most of the participants reported that the text messages were a good way to receive the information when compared with twice weekly email messages. However, for those who rarely received normal text messages, these washing machine messages were disturbing:

H6_{WM} (husband): ‘you know, I don’t get a huge amount of text messages so when I do get a text message I sort of look at it and sometimes it’s only a message from you telling me my washing machine...’

Although we phrased the wording of the text messages as recommendations, we were expecting feedback from participants. In fact, some of them enjoyed receiving texts ‘coming from their washing machine’ while others disliked it for two reasons: some participants did not like being told they had not achieved the best possible while others just resented being told what to do.

H6_{WM} (husband): ‘it’s only 49 per cent and you could have achieved a hundred per cent if you did this, arrh! You know, a little bit, you feel almost a little bit guilty! haha! I don’t want to feel guilty you know’

H14_{WM} (wife): ‘if you send me a text you should put your washing machine on now, I just get very... because I would be just, I think it would just irritate me, hmm other people might take it differently but ...’

We also observed the reverse effect with some participants, where they appreciated the ‘Congratulations!’ message.

Participants also noted the retrospective aspect of these text messages and the fact that they could not act on them as the event was in the past. The only kind of support that can help participants, such as $H14_{WM}$ (wife), is

a fully automated control. She reported being irritated by the text messages because she had already chosen to run the dishwasher (another high energy appliance) at the time suggested to run the washing machine. Thus, the message punished her for doing something unavoidable.

■ *H14_{WM} (wife): 'hmm I didn't find the text messages particularly useful'*

For other participants those text messages were a good reminder, but they found that it came too late to change anything.

■ *H6 (husband): 'when you get the message afterwards it's too late you know you've missed your window.'*

This was also noted by H3_{WM} (husband) who referred to our first intervention (by email). He highlighted the fact that we stopped sending these emails which he had found useful for planning. Without these emails he describes the text messages like getting a result for an exam that he did not study for. H3_{WM} (husband) also compared the Demand-Shifting to '*shooting in the dark*', explaining that they did not have the right type of support to help them achieve a high score:

■ *H3_{WM} (husband): 'what I did find, there is feedback in the text message that 'you ran your washing machine at this time' and 'you were 42 per cent green, the best time would have been... when you would have achieved...' But how would I have known that?'*

For many participants, the interesting element of these text messages was the green percentage of the last load which revealed how much electricity consumed by the washing machine had come from their solar PV. However, the wife in H10 provided an interesting critique on the text message approach:

■ *H10_{WM} (wife): 'unless you're going to keep all these text message and analyse them, you are not going to get that information. Just saying 'your washing used 63 per cent of solar', that's in itself is not really useful to us'*

In this extract, H10_{WM} (wife) explains that it is difficult to reflect on the text message with only the loads of the current day as insight. She notes that she felt she could not learn from the text messages. Although some participants reported that the real-time feedback was useless when they were receiving the texts, many asked us to start sending them again when we stopped the study.

An interesting finding relates to the recipient of the SMS. At first, we asked each household to nominate one mobile phone number which was usually the person most concerned with energy use and who had initially signed up for the wider overall study. Later some of the participants asked us to change the number for some participants or send to multiple numbers. It emerged that the person in the household concerned with energy use was often not the person who was the main washing machine user. From the time we started our study, to

the point where we were sending these messages, these washing machine users who initially concerned with energy use became more involved in the study and more generally in energy issues. For them, the washing machine was a concrete application connected to a routine they cared about. During our interviews we felt much more excitement from these participants than from the usual ‘energy leader’ in the house and this was also something that emerged during focus group meetings.

6.4 PROACTIVE SUGGESTION

Building on our conclusion, we looked for a proactive intervention that would provide information in advance instead of after the event.

6.4.1 DESIGN OF SUGGESTION VIA TEXT MESSAGE

For the third intervention we kept the text messages, but instead of informing users after the load, they received a text message in advance suggesting the best time to run a washing machine load. The aim of this intervention was to help users plan ahead for the best period of solar generation for the current or the following day. Here we wanted to know how users perceived these suggestions and whether they were able to make use of them. Text messages were sent over two months to six participants (182 texts). For this intervention we asked participants to give us the times and days they wished to receive these text messages and we were surprised by the diversity of answers. Of the six participants, some of them asked for a text every day, some others wanted the text messages on specific days, some wanted a message in the morning for the current day and other in the evening for the following day. At the selected day and time for each of the participants, we sent a text message providing the best 2-hour period to run their washing machine. We also noted if the following day would be a better or worse period.

6.4.2 FINDINGS: PROACTIVE INFORMATION IS KEY

The participants were in agreement that the pro-active messages were more useful than the real-time messages, although they noted that they did not always follow the suggestions.

Although only six participants received the proactive text messages, all the participants told us that such text messages would be better than the real-time messages, in order to give them the time to plan and anticipate. For those who did receive the messages, they noted that even if they did not look at or follow the suggestions they felt a sense of appreciation that the information was there for them.

Among those who received proactive messages, we noted two distinct groups. One group did not mind receiving a text every day early in the morning, because they did not have a specific washing day. The other group preferred receiving a text on specific days and would prefer a system that analysed the pattern of their washes and that would send a text in the morning of the most probable washing days. For example, the husband in H8 would like to receive a text on Wednesday, Friday and Saturday:

H8_{WM} (husband): ‘of that day say around 9 o’clock, half eight in the morning, saying ‘washing today at 4 o’clock or 2 o’clock would be a good idea, you would be using x amount’, that would be really useful’

The wife in H9_{WM} made an interesting comment that she needs the text in the morning instead of the evening for the following day. This was in common with others who first chose to receive messages in the evening and changed their minds.

H9_{WM} (wife): ‘because it’s actually on the day itself because I always found there is a differentiation between sending it the day before thinking of that is a great time, I was outside so I didn’t look, so I mean on the actual morning, like sort of pop up at 7 in the morning, we are mostly up and changed, ready for work or schools or whatever’

Although the proactive text messages seemed more useful for the participants, most of them noted that they would prefer a more automatic system that turns on the washing machine at the best time by itself.

H11_{WM} (husband): ‘It would be good like at 7AM in the morning let’s say, you got a message saying ‘today we think the best time to start your washing machine is x’. Yeah that would be useful but I’d probably rather it was one of those to do it for me, you know? I really just wanna put the stuff in the washing machine and say I want clean clothes by 6 o’clock tonight, you do it yourself’

6.5 CONTEXTUAL CONTROL

In order to provide a more ‘automatic’ system, as described by the participants in the previous interventions, we designed a control of the washing machine to shift the load automatically, within a given time frame.

6.5.1 DESIGN OF A WASHING MACHINE CONTROL

The last intervention involved an application on an electronic tablet that could control the washing machine via ZigBee. We present the extended architecture in **Figure 6-6**. In the households, we set up an electronic tablet with a ZigBee USB dongle, allowing it to communicate with the washing machine. Through this communication channel the electronic tablet was able to start, stop and schedule the washing machine, while receiving its status and its selected wash cycle. As the University’s servers could not be accessed from outside, we pushed the latest data (overall electricity generation and consumption, weather forecast) onto an external server at regular intervals. In each household, the application received fresh data every 30 minutes. In

combination with the expected consumption of the selected washing machine load, the tablet generated a suggestion of best time to run the washing machine. A web server and interface managed the user interaction.

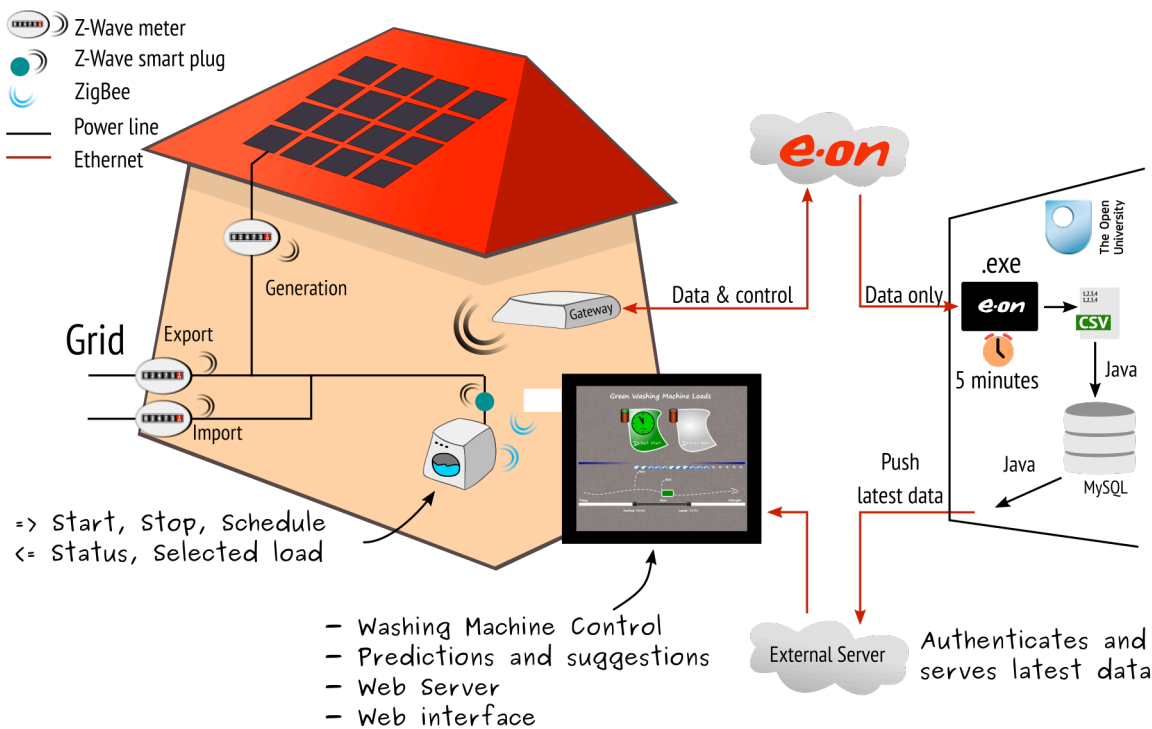


Figure 6-6 Washing machine contextual control – Architecture.

We set up the tablet next to the washing machine (see **Figure 6-8**) as it was meant to replace the washing machine's start button. This interface is the result of several design iterations. The initial interface was an engineering view, meant to replace the entire control of the washing machine and exploiting the ZigBee capability to its maximum. After some demonstration and discussion at a showcase of the department's projects, we realized that the design was too complex, hiding the novel and important functionality. The second design focused on Demand-Shifting with only a timeline representing the coming 24hrs. Circular buttons were distributed along this line at the best times to run the washing machine. The householder could press the most convenient best time. Minimizing the interaction and emphasizing the Demand-Shifting functionality, the design seemed appropriate to be deployed. However, it happened to be harder to explain how it worked to the participants. We collected a wide range of comments from the householders during the installation visits. In particular, they wanted one single but a dynamic best time that would evolve with the weather. They also wanted to see more details about the underlying algorithm and major variables such as sunset/sunrise and weather forecast.

Eventually, we designed an application with the minimum of controls. When the user switched on the washing machine the application woke up and displayed a time line of the day including the flags for ‘now’ and ‘best’ (Figure 6-7). ‘Best’ represents the best time to start the machine, depending on the selected load and the generation and consumption prediction.

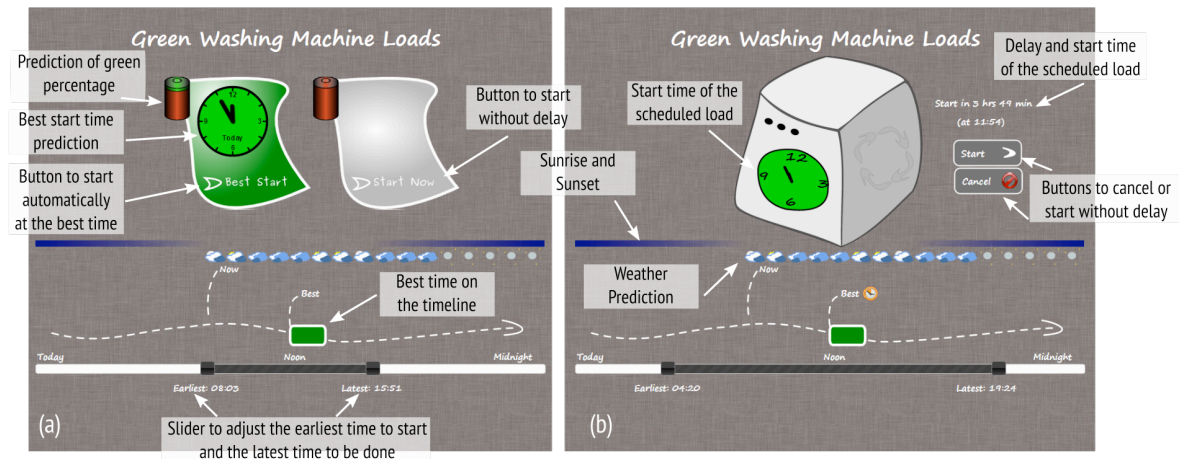


Figure 6-7 Washing machine control. a: Best start button, b: waiting for the best time

A slider allowed the user to define an ‘earliest’ time to start and a ‘latest’ time to finish the load. Then the user chose ‘Best start’ and the washing machine would be started automatically at the best time. Otherwise the machine could be used normally by pushing the button labelled ‘Start now’ which started the washing machine right away. At any time the user was able to ignore our application and use the washing machine as usual. Sunrise, sunset and cloud forecast were used to show the reasoning for the expected best time. Following the focus group discussions with all the participants, we added two battery icons in order to display the estimated amount of energy coming from the grid and from the solar PV for the two given start times. We were able to deploy these update remotely.



Figure 6-8 Washing machine contextual control – Example in situ.

We deployed the electronic tablet with the application in 17 households over three months (one resident declined to use it on grounds of having issues with the design of the washing machine itself). Through this intervention we aimed to observe how an assisted Demand-Shifting application was perceived by householders. Did they use the application? Did it fit with their daily routines?

6.5.2 FINDINGS: CONTROL, INTERACTION AND INFORMATION

Participants' expectations were much higher than what our application was really able to do. Furthermore, as soon as we set up the application in their house, participants came up with various suggestions to further tweak it. For example, in the original set-up, when residents had selected a suitable best time, the washing machine was then delayed and started at the specific time. The first improvement that participants were interested in was to update the best time in case of weather change. They wanted to define an earlier time and a latest start time and say 'Run at the best time in that window of time'. We implemented and deployed this functionality a week after the study begun. The second suggested improvement was about the control during a washing machine load. 'If the generation is suddenly not as great as it was supposed to be, pause several minutes and resume later.' We did not implement this functionality because of the granularity of our weather forecast and because the energy balance: pausing the washing machine when it is heating the water could result in losing energy.

Overall, most of the participants were impressed and approved of the various possibilities the application allowed, including taking account of the selected program cycle to generate a suggestion. They found it easy to select the best time to start the load. In terms of display, some participants would have appreciated more details, which would have resulted in a more complicated display. For example, some wanted to understand how the decision for the best time had been made, perhaps with an indication of what the expected weather for that best time was compared to other times so they could judge for themselves which was better. They also wanted to answer the question: how much better this 'best time' would be compared to running the washing machine now? They clearly wanted to evaluate their convenience against the benefits of shifting the load. This finding echoes existing research on intelligibility of context-aware applications (Lim & Dey, 2013).

H3_{WM} (husband): 'So for example, close to the number 1, at 10:57 in the morning ... But by knowing that we are going to run it at 62 per cent green and that the 2nd option is only 61 per cent green, then I can say I'll take the second because the difference is only 1 per cent'

One major theme that emerged during our interventions was the interaction between appliances, which turned out to be more important than synchronising consumption and generation. A common rule applied by all the participants was ‘Do not run several heavy load appliances at the same time.’ As soon as we started the last intervention with the washing machine application, we received informal feedback from the participants by email and during technical visits saying that they were not making use of the application in the way it was intended, because the suggested time was conflicting with other appliances.

H11_{WM} (husband, by email): ‘I generally use delay start on the machine because the tablet generally suggests a start time which coincides with my heat pump and the hot water cycle!’

It is interesting to note that we received some similar feedback during the previous interventions, but it was much stronger and widespread with the washing machine control intervention. It seems that when participants received the information through text messages they were able to flexibly interpret the information and adapt it to their own setting whereas with the control of a single appliance they were not. In contrast, when the washing machine was not needed, participants reported using the suggested best time of the washing machine application to run another appliance such as the dishwasher or the dryer. Half of the participants described spontaneously what would be their ideal energy management system beyond the washing machine itself.

In H14, the wife is at home most of the time and she already runs her washing machine at a very good time. She represents the ‘best users’ who could only increase their self-consumption with an automatic system. She has in-depth knowledge of the details of the heating cycles of her appliances and wanted a fine-grained sync between the dishwasher and the washing machine. In fact, when the washing machine load visualisation was showing a wash not so green, most of the time it was because the dishwasher was running during this best time. A close interaction between these two appliances would allow her to run them at the same time and pause one of them when the other is heating. Manually this is not really possible, as a normal user can only run them one at a time and they have no control over when each heating cycle begins. Similarly, H16_{WM} (husband) said that he would prefer a system which automatically looks for the best time for the washing machine but also for other appliances such as the dryer and the dishwasher in a priority order:

H16_{WM} (husband): ‘I would like all my free energy to dry my clothes and then if there’s enough free energy left after that I think I’d quite like to maybe wash the dishes’

Beyond interference between appliances, participants highlighted the notion of priority. For example, in H6 the husband would prefer to use his solar energy for his hot water some days when he is back from cycling

(when he wants to shower) while the dishwasher and the washing machine would be a priority on some other days. In H10, the wife reported planning to cook and like most of the participants she does not consider the oven as shiftable. She would like the system to work around this ‘fixed load’. When participants describe their ideal system, they mix situations, lifestyle patterns, information they receive from multiple sources, shiftable and non-shiftable devices, interactive shifting (washing machine, dryer and dishwasher) and fully automatic shifting (hot water, heating system). A central message from participant interviews and focus groups is about being able to change the priority depending on the context.

6.6 DISCUSSION

Through these different interventions, we observed some overarching themes and confirmed some previous work on both the content of the information provided as well as the method and timing of delivery.

6.6.1 DISSEMINATING INFORMATION

In contrast to email interventions that did not generate many specific comments or reactions, our text intervention supports the results of Alan and colleagues (Alan, et al., 2014). This medium seems to be a good interface between a ‘home system’ and householders. However, the content of these texts has to be adapted to the user, following findings of previous studies (He, Greenberg, & Huang, 2010; Woodruff, Hasbrouck, & Augustin, 2008). While real-time feedback appears less useful for advanced users of solar energy, they can be used as a reminder to increase energy awareness.

Participants appreciated the proactive suggestions through text messages. However, the right time to send them is highly variable in day, time and frequency. These parameters should be customised and adapted by the user. While some participants suggested usage pattern (context) detection to send these texts at the best time and day, others appreciated the regularity of messages so they could rely on the information. This shows how people were already developing new routines with and around the new intervention, similarly to the results by Costanza and colleagues (Costanza, et al., 2014).

The way the information was presented across the four interventions brought up further interesting issues relating to time and place and decision making processes around household routines. For most people the emails did not work, as emails were not read very regularly, and often in a dedicated study which may have felt quite removed from where the laundry activity is taking place. In contrast, the text messages were more successful, as typically people carry their mobile phones with them, and would check for such messages

regularly throughout the day. They also use them in all the different places where decisions around washing take place: from washing basket areas, bedroom floors to utility rooms and kitchens. The mobile phone as a device that is often carried with the person is therefore a better medium to carry the relevant information to the user in the right place and at the right time. There was also evidence that the electronic tablets, positioned near washing machines in kitchens and utility rooms were becoming a focal point for communication and that people were making them part of their new routines.

Some households had gone on to using the tablet to control their music, thus integrating the tablet as part of their in-home entertainment, and other households used the information from the tablets to make decisions on running different appliances, like the dishwasher, which were nearby. This issue of time and place is an important one to consider when deciding on UbiComp technologies for the home setting, with each form of communication having its own preferred location as discussed by Crabtree and colleagues (Crabtree & Rodden, Domestic routines and design for the home, 2004).

6.6.2 HIGH-LEVEL INFORMATION

The most useful information for the users was high-level information, for example best shifting time or percentage of green energy instead of raw energy consumption and generation. This follows Mennicken and Huang's definition of a 'smart system' (Meier, Aragon, Peffer, Perry, & Pritoni, 2011) that makes a task better or faster. In the context of local solar electricity generation, it refers to the ability to support three different behaviours: anticipating, reacting and acknowledging. Banerjee and colleagues (Banerjee, Rollins, & Moran, 2011) highlighted the need for householders living in an off-grid house to *anticipate* periods of solar generation. We observed the same behaviour with our grid-tied houses. Proactive text messages that provided the best time to run appliances depending on the solar generation were the most appreciated by the participants. These alerts could also be used to *react*. However, participants expressed the need to know in real time which appliances they could use to adapt their consumption. Doing this manually by looking at PV generation and consumption graphs was time-consuming. Participants noted that the automation provided by the tablet control allowed a precision they could not achieve manually and was a huge time saving. Some participants also used the information to *acknowledge* their own behaviour – to see that they were doing rather well, or treated it as a competition for getting the highest percentage.

6.6.3 WIDENING ENGAGEMENT AROUND ENERGY

Over the study, the flexibility of our system – such as changing phone numbers or customising days and times to receive texts – allowed us to adapt our intervention to each participant and to make it fit with their routine. Clearly participants wanted that sort of flexibility. However, more than highlighting flexibility, it is evidence that household members who were not interested in energy issues previously were becoming more engaged now that the technological interventions related to a routine they tended to handle (washing). In addition, in some households more people became involved in doing the laundry now that it involved use of a smart appliance. This is in contrast to the findings by Kobus (Kobus, Mugge, & Schoormans, 2013) where the division of roles in households seemed to have been more fixed and overall leading to disengagement rather than engagement. However, most importantly the drawing in of more household members into discussions around energy points to this being about an activity, a practice or routine, which people clearly care about. While the wider energy trial had introduced a range of apps and web portals with detailed graphics of energy consumption these had not been of interest to these participants. However, for them the issue of energy balancing became alive when it was tied to the activity of doing the laundry and when they were able to fit it in with nuanced and detailed decision making processes around the home.

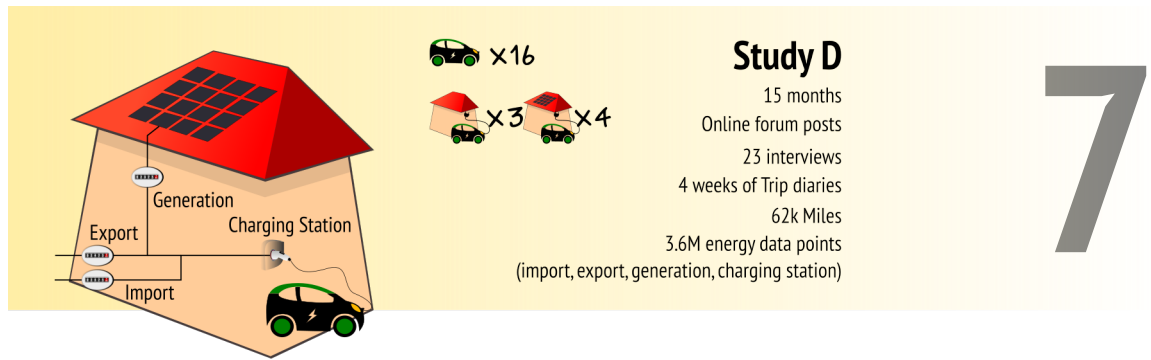
6.7 CHAPTER SUMMARY: TOWARDS PROACTIVE AND CONTEXTUAL SUPPORT

In this chapter, we explored potential user interactions to support Demand-Shifting practices and the relationship between local solar electricity generation and appliance usage. We looked at different levels of information (raw data, computed data, suggestion), time of interactions (past, real-time, future) and medium of communication (text message, email, dedicated display). Technology support for Demand-Shifting is viable and effective. We highlighted that engagement and utility increased from decontextualized information to embedded contextual control, for instance from email to washing machine display. Energy support should move from retroactive feedback to proactive suggestions. In this context, the decisions about timing of washing machine use is *negotiated* with the user.

Our analysis with the participants revealed the complex dynamics between householders, appliances and objectives. Targeting the washing machine leads to a *conversation* with householders who are not managing energy in the house, thus widening the audience and participation. Beyond the technical challenges, the appliances that offer potential opportunities for Demand-Shifting vary between householders and over time.

Finally, maximising the use of domestic micro-generation is one objective among others, including the financial cost and the disruption of the user. Our deployment of user interactions highlighted that predictions and time of interventions were essential to support Demand-Shifting. Interactions based on forecast, planning and suggestion are more appropriate than typical energy feedback. Typical energy feedback providing information about past events fail because there is not much to learn from the past in this context. User support should be proactive and as contextual as possible. Furthermore, a trade-off should be found between manual and automated action to reduce users' effort without reducing their engagement. Through these interventions we reached the boundaries of the single-appliance study. While it provided key insights to understand the laundry routines, our interventions revealed strong interactions between appliances making difficult the intervention on a single appliance.

In Chapter 8 we will formalise all these insights into a conceptual framework. However, we wanted to strengthen our insights to build a more complete framework to support Demand-Shifting practices. Supporting this aim, the next chapter looks at electric vehicles (EV) and emerging e-mobility. The significant differences of size, time of use and flexibility between the washing machine and the EV make it the perfect case to extend our model.



Looking at a New Form of Home Electricity Consumption

Electric Vehicle and e-Mobility

*‘They always say time changes things,
but you actually have to change them yourself.’*

ANDY WARHOL, CHAPTER 7, *THE PHILOSOPHY OF ANDY WARHOL (FROM A TO B & BACK AGAIN)*, 1985

Through studies A, B and C we provided a deep understanding of the relationship between local solar electricity generation and laundry routines. It is crucial to support these emerging engagements, which can potentially go beyond Demand-Shifting towards more responsible energy behaviours. However, we also pointed out the small benefits of shifting the time of washing machine loads. In this chapter, we look at a new form of home electricity consumption, the Electric Vehicle (EV), which contrasts with the washing machine by its high electricity consumption. Like the washing machine, the car has been part of a core routine – that of mobility – in most households for decades. However, the EV is a new form of home electricity consumption which comes with characteristics that push householders to alter their established mobility routines. This is an ideal setting to observe and discuss daily routines and emerging practices. We extend our understanding of the local generation context while opening up a new form of electricity consumption. To achieve this goal, we implemented the Participatory Data Analysis (PDA) presented and implemented in Chapter 5.

7.1 EXPLORATION: THE EV CONTEXT

Looking at the EV extends the boundaries of this research project to the electric mobility domain. In this section we aim to understand the challenges of EVs and potential connections between EV and Demand-Shifting. We used insights from online EV communities and the perspective of existing EV literature to

conduct exploratory interviews with EV driver with different levels of expertise. We shed light on a research gap at the intersection of the EV, home and solar electricity generation.

7.1.1 EXPLORATORY INTERVIEWS

Online EV community

To get an initial flavour of the main discussions that arise at the country scale about EVs, we looked at the two online British EV forums SpeakEV and LeafTalk. It was a way to reach quickly people from different regions in the UK and gather information passively, without the researcher's intervention. The only interaction we had on the forums was to present ourselves, our work, and ask for participants' to volunteer for the exploratory interview we detail in the next section. We only looked at discussion taking place before our registration to the forum. We simply observed what members were discussing; they posted by themselves without any initial prompts (other than those from other forum participants). We considered the ethics of looking at such data in the perspective of Convery and Cox's guidance (Convery & Cox, 2012) and assessed there was no need for consent forms as we performed a light and general analysis of publicly available, non-confidential, non-vulnerable data without potential harm or intrusiveness.

Our goal was to get a sense of the main discussions and collect the necessary key insights to inform our exploratory interviews. In this exploration we generated cloud of words and we read posts that we had prioritised based on key words related to solar PV and names of EV tools we knew. Discussions were dominated by issues that EV drivers reported. This reading gave us initial keywords to search for more details, especially technical and practical information which helped us expand our knowledge faster. This came in parallel with our knowledge from the literature. We used these insights to build the guidelines for our semi-structured interviews. These interviews explored what living with an EV means on a daily basis. At this stage we did not frame our exploration to local generation particularly. In contrast with the washing machine, it was important to look at the electric mobility first as a whole to capture all its aspects.

Participants

We conducted interviews with 16 EV households from around England (**Table 7-1**). Seven of the households (H1_{ev}-H7_{ev}) were part of the 'Greener miles' group of the E.ON trial presented in Chapter 3. We recruited the others through leaflets we placed on the windscreens of EVs that we came across in various car parks, through our project website and the online forums explored in the previous section. Every participating

household had a full EV (Nissan Leaf or Renault Zoe) although one had a Vauxhall Ampera which is technically a full EV with a fossil fuel generator to extend range. Some of them were also involved with EVs through their professional life such as energy policy consultant, EV retailer or transport council member. Participants were all middle or high-middle class households, and varying in age, with some working from home, some working away from home and others retired. They all had access to domestic charging, the majority (10 out of 16) had solar PV on their roofs and while most were on a fixed rate electricity tariff a small number of households paid through the Economy 7 tariff where electricity consumed during the night hours is significantly cheaper than when consumed during day hours.

Table 7-1 Study participants. Greener Miles households (H1-H7) and EV participating households recruited in England (* Plug in Hybrid EV)

	Household	Work distance	EV user	PV	EV	Tariff
H1_{EV}	2 adults, 2 children	Retired	Shared	No	Leaf	Fix
H2_{EV}	2 adults, 2 children	Long commute	Single	3.2kwp	Leaf	Fix
H3_{EV}	2 adults, 2 children	Work Locally	Shared	No	Leaf	Fix
H4_{EV}	2 adults, 2 children	Work Locally	Shared	7kwp	Leaf	Eco7
H5_{EV}	2 adults	Long Commute	Shared	3.2kwp	Leaf	Fix
H6_{EV}	2 adults	Retired	Single	1.9kwp	Leaf	Fix
H7_{EV}	2 adults, 2 children	Work Locally	Single	No	Leaf	Fix
H8_{EV}	3 adults	Work Locally	Single	No	Leaf	Fix
H9_{EV}	2 adults	Work Locally	Single	Yes	Leaf	Fix
H10_{EV}	2 adults, 2 children	Work Locally	Shared	Yes	Ampera*	Fix
H11_{EV}	2 adults	Work Locally	Single	Yes	Leaf	Fix
H12_{EV}	2 adults, 2 children	Work Locally	Shared	4kwp	Leaf	Eco7
H13_{EV}	2 adults, 2 children	Long Commute	Shared	Yes (large)	Zoe	Eco7
H14_{EV}	2 adults, 2 children	Work Locally	Shared	Yes	Leaf	Fix
H15_{EV}	2 adults, 2 children	Long Commute	Shared	No	Leaf	Fix
H16_{EV}	2 adults, 2 children	Work Locally	Single	No	Leaf	Fix

Interviews

We conducted the interviews in December 2014 and January 2015. They took place at participants' homes when it was possible, otherwise we went to participants' work places, we invited them at the Open University or we conducted the interview via Skype. We structured the interview in four steps:

- General – We wanted first to know more about the participating households. We asked questions such as 'Who lives in the household?' or 'How much time is spent there [at home]?', but also questions about their motivation for participating in the study and how they talk about energy in the household.

- EV – We then centred the discussions around motivations, behaviours, attitudes and experiences of EV usage and charging. In general terms, how they describe their use of this particular car, the different issues but also the things they enjoy.
- PV – As main topic of this whole research project, we led the discussion into electricity consumption and local generation. For those would had solar PV, we tried to sense their motivation, their usage and how they were connecting consumption and generation. This was far more general than the participatory study of study B. For those without solar PV, we were interested in whether they had thought about having local generation and the motivations or the reasons why not.
- Wrap-up through pictures – As a final step, we presented two sets of pictures we built from our exploration of online forums. First, we went through a series of interfaces of existing EV or energy related tools. Our objective was to collect comments on these tools, the features they use or not, and lead them talking about other tools we could have missed. Second, we used a series of pictures showing typical activities such as doing food shopping, charging the car, being in family, having a coffee, etc. Depending on the interview setting, the pictures were spread on a table or shared with Skype participants in an online gallery of pictures.

In total, we audio recorded 15 hours of interviews. We transcribed them and performed a thematic data analysis. To diversify our experience with tools, we used NVivo instead of the Latex extension ULQDA used in the previous studies. In the context of thematic analysis of transcribed content, both tools provide the necessary features for encoding and exploring the data through graphs which revealed various common experiences that were emphasised by the different participants.

7.1.2 THE EV AS A NEW FORM OF HOME ELECTRICITY CONSUMPTION

In this section we highlight our findings from the exploratory interviews from the perspective of the literature to build an overview of the EV as a new form of home electricity consumption.

Motivations

All of the interview participants mentioned financial benefits as their primary motivation for their decision to purchase an EV. This decision has often been based on detailed financial calculations where they have incorporated knowledge of past mileage to compare electricity costs with fuel costs. However, at the same time many participants emphasised that for them electric mobility provides a way to combine financial benefits with reduced environmental impact and greener driving.

The fact that EVs stand for cleaner technology than combustion engine cars was stressed as a factor that adds value to their ownership and usage. Some participants emphasised that awareness of environmental

implications has not been there from the very beginning, but was only developed over time as energy issues have moved to the foreground through the experience of using an EV.

H5_{EV} (woman): ‘so the incentive of the money is a good incentive to start with and then you think about all the other implications and obviously understand how it's beneficial for energy as well as for your wallet.’

In particular, EVs are perceived as a means to achieve energy independence and become more autonomous from inflexible energy supply systems. In this context, the participants report on a much greater freedom of decision-making, whether it concerns the decision to charge EVs at home or at public charging points, use conventional or renewable energy sources or choose among specific time-of-use energy *tariffs*. Also, battery storage capacity provided by EVs is seen as an opportunity for novel energy saving behaviours which have not been possible before.

H10_{EV} (Wife): ‘So what happens to that energy you can’t store because you haven’t got battery storage so it goes back into the grid and basically the large energy companies in the UK which are the six big ones they got this deal stick very nicely for themselves.’

EVs are widely promoted as a green mobility solution and the literature indicates that pro-environmental orientation is a major factor for adoption of EVs. In a before/after study conducted as part of an EV trial (Bunce, Harris, & Burgess, 2014) 39% of participants stated CO₂ emissions as an important purchase factor before the start of the trial but this figure rose significantly to 92% after the trial. This resonates with our findings. EV Drivers understood the potential for EVs to reduce carbon emissions, but realised this can only be achieved by the use of electricity from sustainable and renewable sources. Similar studies (Graham-Rowe, et al., 2012; Vilimek, Keinath, & Schwalm, 2012) indicate that drivers have a strong desire to power their EVs with electricity generated from renewable sources and are uncomfortable about the current green credentials of EVs.

Charging an EV

There are multiple options to charge an EV in terms of rates, locations, prices and times. An EV can be charged either (i) on a standard home socket, (ii) on a ‘normal’ charging station at home or away – about 7 minutes for each mile of driving capacity, or (iii) on a rapid charging station that can reach 80% charge within 30 minutes. All of our participants had a ‘normal’ charging station at home while some were also able to use a connection at work or a shopping centre car park. Home charging costs about 6p per kWh at night if users have the Economy 7 tariff (night and day tariff) and about 12p per kWh all the time otherwise. Outside the home drivers need to carry an RFID membership card for each system they might wish to use. Each

commercial system requires a membership and charge at an hourly rate of £1-1.70 for ‘normal’ charging (20-30x the cost of home charging). At time of writing, one company offered unlimited free (with membership card) use of its rapid charger network at IKEA stores and major motorway service stations while another company charges £7.50 for 30 minutes (7-8x the cost of home charging).

Intercity trips require much more planning. If the driver plans to park in the city for any length of time they can try to obtain membership in that city’s commercial scheme if their own membership does not cover it. For a long journey this requires the user to find the first rapid charger within about 60 miles of their starting point and ideally a back-up choice in case the chosen point is occupied or out of order. Many UK users post major charge station status updates to twitter with the hashtag #ukcharge while websites such as www.OpenChargeMap.org and www.PlugShare.com allow users to post locations of known working charge points and their status and access requirements. This allows private and hidden charge points to become available. For example, PlugShare shows locations of people willing to let other EV drivers use their home charging station. This leads us to the vast range of existing tools detailed in the next section.

ICT tools

The participants refer to a wide range of apps and tools that can be used outside of the car to increase the amount of information about their EVs and home energy systems. The interviewees express a keen interest to connect to their cars and check car status information or change control settings.

Beyond looking at in-car dashboards, the participants refer to apps and tools that can be used outside of the car to increase the amount of information about their EVs and home energy systems. The interviewees express a keen interest to connect to their cars and check car status information or change control settings. The owners of Nissan Leafs talk about the Carwings app which runs on a smartphone and lets them start charging, retrieve current state of charge and range or activate heating. For users of other car models, such as the Renault Zoe, apps with similar functions are available.

To support trip planning, participants emphasise the lack of dedicated support tools which forces them to manually combine required information from different sources. Google maps is used to get an estimation of distances between stops or end points of a trip. Online tools such as ZapMap or OpenChargeMap provide map overlays that display the location of public charging facilities. Some users also check Twitter for specific

hashtags or look at EV user forums to be warned of any charging point failures or learn of best practices of other drivers.

Participants with solar PV installations are keen to record historic electricity generation or have smart meters and apps that can be used to access real-time electricity generation. They use this information to judge the payback of their investment or decide about best times of the day to switch on household appliances in order to maximise the use of solar energy. Some participants have installed more sophisticated tools which come with energy feedback to direct their behaviours in a more targeted way.

H15_{EV}: ‘The system at the moment, it sits in the hall as a big display which basically is green if you are generating and red if you are using. So if it goes green you can just go and switch on the dishwasher because you know you have got free electricity. And if it’s red, you can delay it until the sun comes out.’

However, the interviewed EV users miss tools that are able to combine information on home energy and EV to improve the transparency of energy which is stored on the cars’ batteries. In particular, participants are keen to understand the mixture of the energy in the car’s battery in terms of energy sources to help them create awareness about how well their behaviour matches their goal of using renewable or cheap energy. Currently, users can only take an educated guess as reliable information which can provoke or amplify any behaviour change is missing.

Charging Experience and Confidence

A wide range of charging preferences were expressed which are shaped by individual mobility needs, e.g. the distance of commutes to work. Common to all participants are however negative experiences with public charging infrastructure. The participants developed a lack of confidence in the reliability of public charging points, caused by various uncertainties, e.g. blocked parking bays, broken chargers, non-readable charging cards, incompatible sockets or charging cables that caused their public charging attempts to fail or be delayed.

H12_{EV}: ‘and it’s because the infrastructure is inadequate. if you go to a service station you may find the charger is faulty when you get there. if you are depending on that, if you haven’t left enough to get to the next charger, you’re dead.’

After an initial negative experience with a faulty public charging station, H7_{ev} even stopped using his EV for all longer trips that would exceed the maximum range of his car. In contrast, participants expressed a high confidence in private charging, whether it is charging at their own homes, at work or at friends’ places. Especially, home charging is considered to be a convenient way as it provides a great deal of control and

certainty and allows for either immediate or time-shifted charges (in case of Economy 7) whenever they arrive at home.

H5_{EV} (woman): 'all we do is just the plug in at the front. we don't control timing wise, we just wait until it gets to 20/30 miles range left, put it in the garage overnight, plug it in and then take it out in the morning and it's charged.'

The decision whether to charge at home is often also driven by cost savings. While previously public charging has been entirely free of cost, local charge point operators such as Charge Master have recently started to introduce costly pricing scheme so that many of the participants make less use of public charging for everyday usage now. Only for long distant trips or trips away from home, public charging is often found to be without alternative. To increase the opportunities of home charging, H14_{ev} has even built his own network of domestic charging points by asking friends without EVs to install domestic charging stations in their garages where his car can be charged during a visit.

These findings only echo a growing literature on HCI issues related to EVs (Burnett, 2009; Franke, Trantow, Günther, & Krems, 2014; Lundström & Bogdan, 2013; Lundström, Bogdan, Kis, Olsson, & Fahlén, 2012; Richard, Lubart, & Vaillant, 2014; Strömberg, et al., 2011) dealing for example with issues such as drivers worrying about whether their battery will last long enough to cover the distance they need to travel, referred to as range anxiety (Franke, et al., 2014; Franke, Trantow, Günther, & Krems, 2014; Monigatti, Apperley, & Rogers, 2014; Lundström, 2014; Lundström & Bogdan, 2014; Loehmann, Landau, Koerber, & Butz, 2014) or how to plan their route so that there are sufficient charging points (Lundström, Bogdan, Kis, Olsson, & Fahlén, 2012).

Most of this research views the EV as a car that is hampered by limited range and the need for frequent recharging. Thus, most of this work is primarily focused on remedying perceived shortcomings and helping EV drivers deal with their cars' limitations on an emotional and/or cognitive level (range anxiety, range prediction, route planning). However, in the context of this research project, it is really interesting to observe the high confidence of charging at home. In fact, the more EV drivers charge at home, the more opportunity to use the domestic micro-generation.

7.1.3 SUMMARY: RESEARCH GAP CONNECTING HOME AND EV

In this section we explored the context of EV and PV through exploratory interviews and we set these findings in perspective of the existing literature. Our findings echo some well-established facts, especially in terms of motivation and public infrastructure. However, up to now research has treated home energy and EVs as separate topics. In the EV literature the home and the household have been virtually invisible, despite the fact that home- and work-life fundamentally shape the demand for mobility. The relationships between household members, as well as those between them and outside organisations (school, employer), other people (friends, boss) and locations of significance (home, school, workplace, shopping centre) need to be explored to understand to what extent a sustainable lifestyle is desirable/feasible – or why not. In the next section, we investigate EV usage as an extension of home and work life to understand the desirability and feasibility of powering EVs with domestic solar electricity.

7.2 ANALYSING: SOLAR GENERATION AND EV

In this section we look at home electricity and mobility data to observe the gap in time and power between local solar electricity generation and EV consumption.

7.2.1 DATA COLLECTION

We collected home electricity data in seven households through the infrastructure presented in Chapter 3 (p. 60). As part of the E.ON ‘Greener Miles’ group, these households (H1_{EV} -H7_{EV} in **Table 7-1** p.127) received a Nissan Leaf through a favourable lease for two years. Among them, four households had solar PV on the roof (H2_{ev}, H4_{ev}, H5_{ev} and H6_{ev}). Similarly to the studies B and C, we logged the power imported from and exported to the grid and the power coming out of the solar PV. In addition, each participant had a charging station to charge their EV at home. We were able to log the power consumption of this station, thus were able to detect home charging events and the amount of power drawn by the EV at home. Unfortunately, the energy monitoring was interrupted after this point due to safety concerns: the meter of one EV charging station caused a short circuit and no better and safer replacement could be found.

To source information on households’ EV mobility behaviours, we accessed data from Nissan’s telematics service known as ‘Carwings’. The Carwings data provided us with daily trip information such as mileage and energy consumed for each trip. With the collaboration of H4_{EV} as test bed, we have made several attempts to increase the level of details of our data by collecting GPS logging and more precise information on charging

and trip events. We set up an OBD-II device (On-Board Diagnostic) in the car design to scan information of the car in real time. This would have provided real-time fine-grain information on charging and trip events. Connected to a smartphone via Bluetooth we were able to send real-time data to our server. The smartphone was providing the communication but also the GPS information. However, we encountered two issues:

1. The whole set up was consuming too much power. The phone was running out of power after few days because the trip's period (when the car was ON) was not enough to top it up. A permanent connection to the 12V battery fixed this issue. However, H4_{EV} got locked outside his car once because the 12V battery was empty.
2. Some participants were opposed to such a setup for several reasons including privacy issue, fear of the car warranty or bad feedback read about OBD-II on the Internet.

As a result, we did not deploy the logging system in all participants' cars. We focused our quantitative analysis on Carwings mobility data in combination with E.ON energy data. In this section we look at EV mobility and the home electricity separately before analysing the potential of powering the EV with local solar electricity generation. Through this quantitative work relying on few households, we only aim to provide some insights on the home energy ecosystem in the context of EV and PV.

7.2.2 EV MOBILITY

Our logs from Carwings covered a 15-month period (436 days) from October 2013 to December 2014. This represents 11,032 EV trips covering 62,856 miles. The analysis of these data helps characterising daily EV usage of the seven participating households. Throughout this section we attributed a colour to each household.

Figure 7-1a shows the distribution of number of trips a day for each participating household over the entire period. For example, the yellow line shows that H3_{EV} has regularly four trips during the day with a hundred of days following this pattern. We notice the decreasing even peaks as most trips are in pairs. Moreover, there is a high fraction of days (26.3%) combined for all households with no trips at all where the cars were parked and stayed still. Though, this information should be considered with caution as 'no trip' can also translate a failure to record on a particular day. Overall, since EVs are often used for short and opportunistic trips around the city, we can see that EV usage sums up many trips on single days. Especially, H3_{EV}, H4_{EV} and H7_{EV} that represent employed households with children have a wide distribution of daily trip activities and frequently

use their EV for four or more trips a day. While $H2_{EV}$ and $H5_{EV}$ are also households with regular employment, they have to perform longer daily commutes and use their EVs often for 2 trips a day only. $H1_{EV}$ and $H6_{EV}$ are retired households with a restricted mobility demand in the range of 2-4 trips a day.

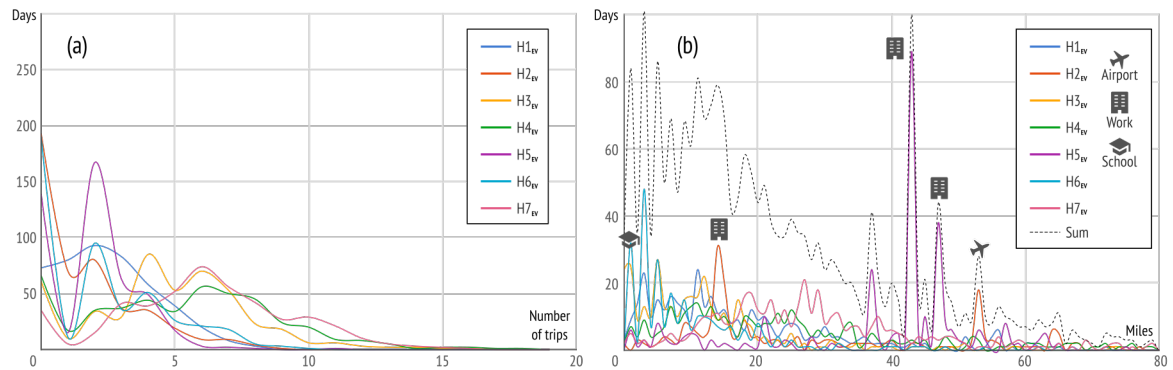


Figure 7-1 EV mobility. a: for each participant, number of trips a day, b: the number of miles a day

In comparison, **Figure 7-1b** presents the distribution of miles a day for each participant. This chart focuses on ‘driving’ days, leaving out the 26.3% of non-driving days (841 days) mentioned above. This chart complements the information provided by the number of trips. For instance, the regular 2-trip a day of $H5_{EV}$ stands out because of a high concentration of longer-distance trips caused by daily commutes of the two household members to workplaces outside Milton Keynes. Thus, this is a combination of different 2-trips a day. We also learned during the interviews that one of them changed her job, generating the third peak. Other households’ mobility radius is smaller and most often restricted to intra-city distances, given a high density of daily trip distances of no more than 7 miles ($H3_{EV}$ and $H6_{EV}$) or maximum 17 miles ($H1_{EV}$ and $H2_{EV}$). The sum of all participants’ days (grey dotted line) emphasises these small distances. Yet, it is important to flag most participants have a second car. These small distances do not necessarily fully reflect the household mobility. $H4_{EV}$ and $H7_{EV}$ have a wider distribution of daily mileages which is characteristic of their need for being flexible about their mobility behaviours due to changing roles and responsibilities in their jobs and lives. Sometimes, the households used their cars for journeys to remote destinations at greater distances, e.g. to travel to the airport ($H2_{EV}$ and $H4_{EV}$) or visit relatives and friends in other towns ($H1_{EV}$). Making the link with the qualitative data presented in the next section (§7.3), we annotated some of the typical events which became obvious after our interviews. Wrapping up this first analysis, $H4_{EV}$ realised the longest trip of the entire period on August 8th 2014 with 75.8 miles. Considering this value as the empirical maximum capacity, we highlight that 75.7% of all days driving distance was below the half of the EV battery capacity (37.9 miles) while the median of daily driving distances was 18 miles.

7.2.3 HOME ELECTRICITY

In study B (Chapter 5), we looked at the overall electricity consumption and local solar electricity generation along with the washing machine electricity consumption. In this section, we perform further analysis of smart meter data to understand the implications of households' EV usage for the home energy ecosystem. Due to the safety recall of the domestic charging station meters, we conducted this analysis over a 10-month period from September 2013 to June 2014, when both Carwings, smart meter and charging station logs were available. In our analysis we ignored a number of faulty days when one or several meters reported incoherent data. Our checking included for example solar generation at night or greater than the participant maximum capacity, export greater than generation.

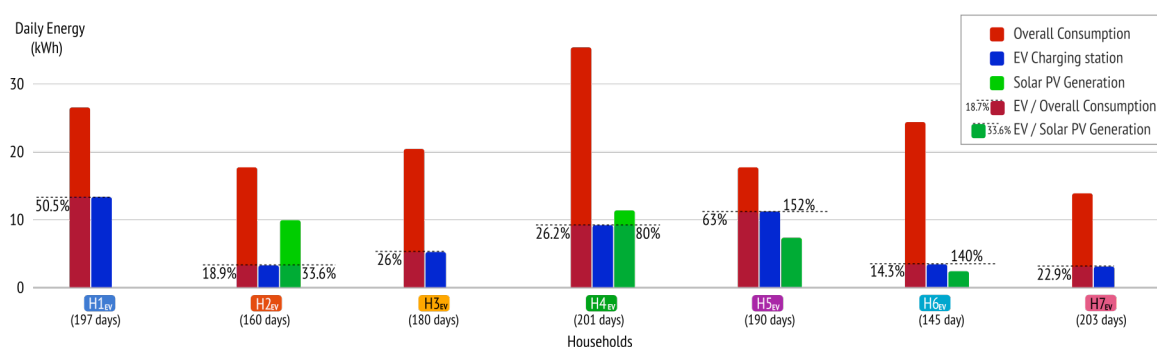


Figure 7-2 Daily overall consumption, EV charging station consumption and solar PV generation.

Figure 7-2 displays overall household electricity consumption (in red) against electricity expended for home EV charging (in blue). EV charging introduces a significant overhead to home electricity consumption. Combined for all households, the average electricity consumption spent on charging the EV at home represents 27.2% of the overall home electricity consumption, with H1 reaching 50.5%. This can be set in perspective to the washing machine average consumption which represented 1.8% of the overall consumption (Chapter 5). Aside the overall and EV consumption, we depict the amount of generated daily electricity (in green) of the four households with solar PV. We can observe the average daily generation is higher than the average daily EV home charging for H2_{EV} and H4_{EV} while it is lower for H5_{EV} and H6_{EV}. This is expected, knowing H5_{EV} is a heavy commuter and H6_{EV} has a small solar PV array. It is important to note that the availability of solar electricity is strongly affected by seasonal variations. This comparison between EV home charging consumption and local PV generation needs to be unpacked and studied in more details.

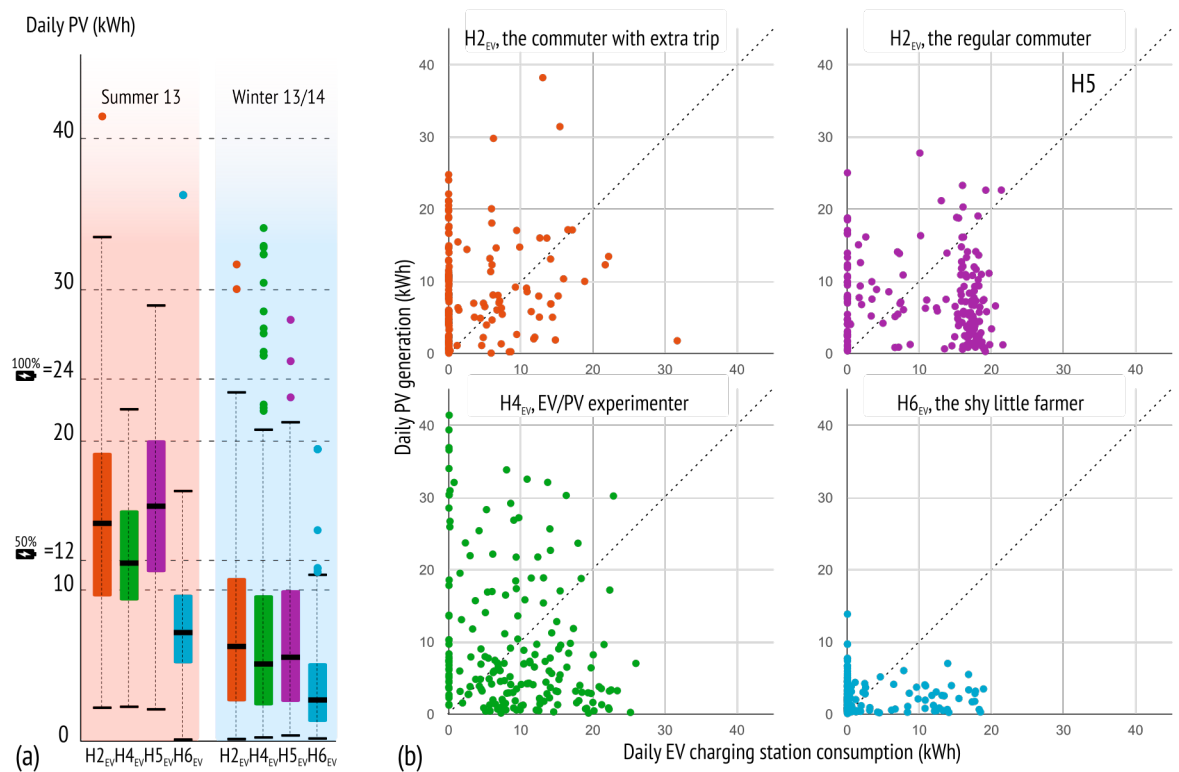


Figure 7-3 Mapping of EV and PV energy in the home. a: the distribution of daily PV generation of PV households in summer 2013 and winter 2013/2014; b: the daily EV home charging demand versus the daily local solar generation. Note: the battery icons on the y-axis provide a reference to the battery capacity of the Nissan Leaf (24kWh).

Figure 7-3a compares the distribution of the daily PV generation over the summer 2013 and the winter 2013/2014. For this specific chart, we looked at valid days between April 2013 to April 2014 to have view over a complete year, as the PV generation logs were available over all this period. Setting this chart in the context of the Nissan Leaf's expected capacity and driving efficiency of 24kWh/75miles, we marked the energy required for 50% and 100%. We can observe none of the household's PV generated half of the EV battery capacity on a regular basis over winter months (October to March), though, it did provide 5.7kWh which translate to about 17.8 miles. In contrast in summer months (April to September) the median of all participants but H6 reaches the half capacity of the battery. Thus, participating household with solar PV and EV electricity generation are not able to get a full EV battery charge (24kWh) every day at home. However, we highlighted in the previous section that in practice the daily EV needs (from home charging station) are well under the full charge, making EV electricity consumption and solar PV generation of similar magnitudes. We note the number of outliers for H4_EV (green) over the end of winter 2013/2014 that reflect the household's PV upgrade from 4 to 7 kwp happened in March.

To explore this similar magnitude in practice, **Figure 7-3b** compares daily household electricity generation with daily EV electricity consumption, with each scatter plot depicting one of the 4 EV/PV household and

each dot representing a single day. Dots on the diagonal indicate days where electricity demand from EV driving exactly matched home electricity generation. Dots above the diagonal represent days when electricity generation exceeded EV electricity use (we call this an ‘energy-positive day’) and dots below the diagonal represent days when electricity generation was less than EV electricity use (i.e. ‘energy-negative day’). While all households exhibit both energy-positive and energy-negative days, we can observe significant differences between participating households. The percentage of energy-positive days is 79% for H2_{EV}, 43% for H4_{EV}, 38% for H5_{EV} and 67% for H6_{EV}. However, this view of energy-positive day is biased by the number of non-charging days: days when no EV charging happened at home. These days creates the line of dots on the y-axis. The percentage of energy-positive and charging day is 17% for H2_{EV}, 25% for H4_{EV}, 14% for H5_{EV} and 11% for H6_{EV}. H2_{EV} and H5_{EV} show similar generation patterns (they have identically sized solar PVs) but because of H2_{EV}’s more moderate mobility demand H2_{EV} has many more energy-positive days. H4_{EV} and H6_{EV} show diverging patterns and this highlights a wide range of differences between them: H4_{EV} has a large mobility energy demand but also generates a lot of energy, while H6_{EV} has a small mobility energy demand and also generates comparatively little energy. H6_{EV} has the smallest solar installation (1.9kWp) while H4_{EV} has the largest one (7kWp). Complementing this technical view with qualitative insights, H6_{EV} is a retired couple which took part of the EV trial as a ‘why not’, far less involved than H4_{EV}, a very active family engaging and experimenting with both the EV and the PV. We characterise them as the ‘EV/PV experimenter’ versus the ‘shy little farmer’.

7.2.4 EV CHARGING WITH SELF-GENERATED ELECTRICITY

The data demonstrates a variable but significant potential of powering EVs with self-generated electricity. However, the analysis ignores the asynchrony of home generation and EV demand. We already raised concerns about the difference between energy-positive days with and without consideration of EV charging during that day. It flags both medians and means are biased over a multi-day period. Unless the homes have a battery for storage of solar electricity (which currently they do not), the solar electricity cannot be directly used for EV driving.

To explore this timing issue in depth, **Figure 7-4** presents the distribution of charging events during and within days in contrast with the local solar generation of the four PV households. The y-axis represents the days while the x-axis represents the hours in those days. The weekends are marked in light brown for

reference. The scale of green represents the distribution of solar generation produced by each household. On top of that, red lines represent the EV home charging.

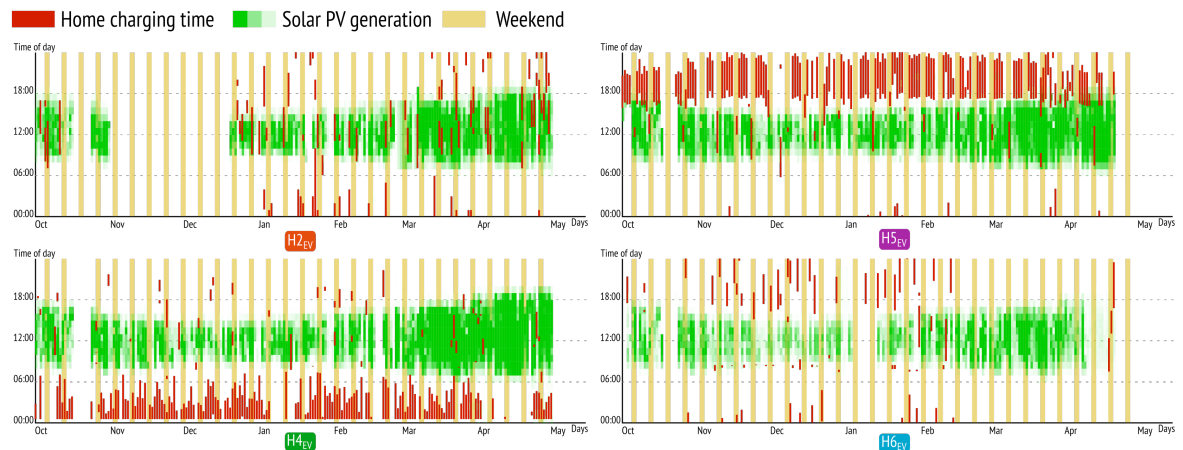


Figure 7-4 Distribution of charging events during and within days versus PV generation.

At first glance, we can see again that each of the four households have very different patterns. H5_{EV} plugs the car in around 6P.M., when arriving at home, making sure the car will be ready for the following day. Though, we notice an attempt to charge the car when the sun is out over the weekends. A timer systematically starts charging H4_{EV}'s car at half past midnight, fitting with the Economy 7 tariff. Both H5_{EV} and H4_{EV} are heavy users of the car (inferred by the home charging) which contrasts with the sporadic use of H2_{EV} and H6_{EV}. While H2_{EV} and H6_{EV} could also charge away and bias this view, our qualitative data confirms they do most of their charging at home. From these detailed views we clearly see the asynchrony between local solar electricity generation and EV home charging. We found that currently only a fraction of the electricity for EV home charging comes from solar: 25% for H2_{EV}, 2.4% for H4_{EV}, 3.5% for H5_{EV} and 1.3% for H6_{EV}. These figures are far-off the comparison between the daily generation and the daily EV consumption presented in the previous section but accurately reflect the actual green mobility.

7.2.5 SUMMARY

We provided a detailed and combined view of domestic electricity and EV mobility data. We emphasised very contrasted observations between aggregated values such as the daily energy values for each household and the detailed values. While aggregated values show similar magnitude between the domestic EV charging and the domestic micro-generation, only a little fraction of this local generation goes into the car. While it might appear there is a great opportunity for improvement, it might also translate to the inflexibility of mobility routines. In the next section we rely on this initial quantitative analysis to understand EV usage and mobility flexibility in collaboration with the participants.

7.3 DESIGNING: THE MOBILITY CLOCK

With a richer view of the data in mind, we observed that there is a potential for improving the domestic energy gap by shifting EV charging events in time towards a better solar generation period. However, this potential fully relies on householder behaviours and when they use their car. To understand the behavioural opportunities of closing the self-sufficient mobility gap we need to explore the reasons why EV drivers exhibit the observed mobility behaviour and how flexible mobility behaviour is.

From (location)	on (day)	at (time)	To (destination)	at (time)	People in the car	Purpose of the trip
CITY	22/1	3:00pm	HOME	3:10	1	RETURN FROM CITY
HOME	23/1	8:15	SCHOOL + RETURN	8:35	2 out 1 B4V	SCHOOL RUN
HOME	23/1	9:15	NEIGHBOURS	9:30	1	TO GYM
NEIGHBOURS	23/1	11:30	CITY	11:40	1	TO SHOP
(a) CITY	23/1	12:30	HOME	12:40	1	HOME

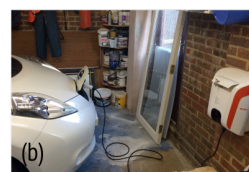


Figure 7-5 Collecting data. a: a sample of H1's trip diary, b: H4's car connected to the home charging station

Failing to collect detailed e-mobility data, we conducted a paper-based diary study to enrich the automatically monitored vehicle data with insights about contextual trip information and charging activities including the purpose of the trip, accompanying passengers, as well as trip start and end location (e.g. home or work). We asked EV drivers to record this information on a paper-based form located in each EV. **Figure 7-5** shows a sample of H1_{EV}'s. To remind the participants of keeping a continuous log, we asked them to place a paper copy of the diary form in their EV so that they could fill in all details straight away when they have completed a trip. The diary study started at the end of January 2015 and lasted four weeks. We later realised that our plan B – that of trip diary – provided us with much richer and personal data than we would have obtained through automatic logging.

We created behaviour visualisations that use a 24-hour clock metaphor, which we call a mobility clock (**Figure 7-6**). The mobility clock represents the spatiotemporal e-mobility behaviour of a household. The home is located at the centre of the clock (indicated by a house icon). EV journeys are represented by arrows, with the distance between the home and end points indicating the relative driving distance. A point located at the outer edge of the clock indicates a journey end-point furthest away from home. The start and end times of trips are indicated by their position with respect to the clock times. For example, the mobility clock on the **Figure 7-6c** (H4_{EV} on February 12) shows one trip between 8P.M. and 9P.M. from home to the airport and back, with three trip segments. Destination icons indicate the purpose of a trip, for example school run,

commute, pick up and drop of children. When available, the names of accompanying passengers are indicated next to the arrows. This trip information was derived from trip diaries recorded by the participants.

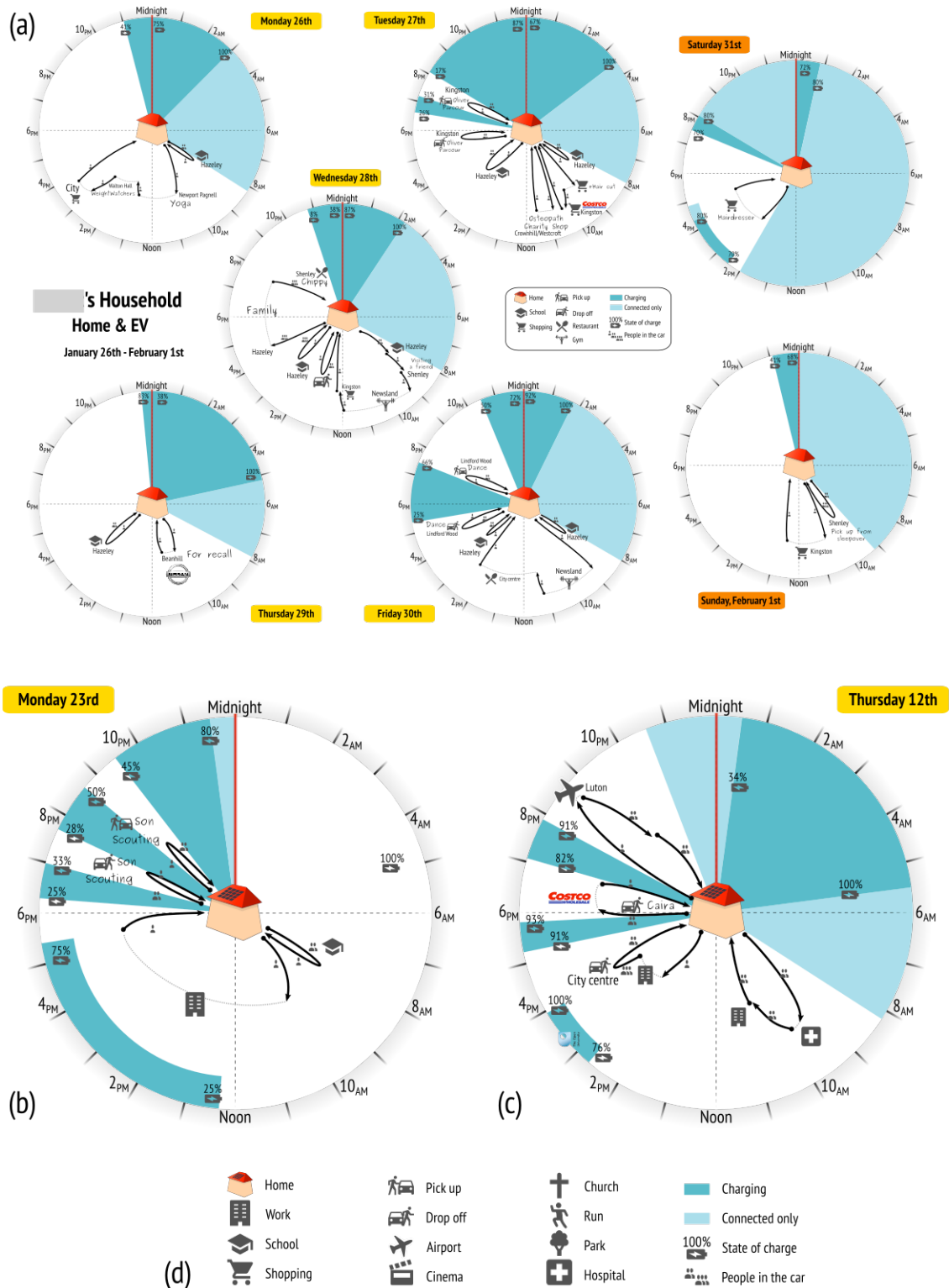


Figure 7-6 Mobility clock. a: Overview of H1_{EV}'s EV mobility between Feb. 26th and Mar. 1st, presented to the participant on a A3 sheet; b: zoom in H2_{EV}'s EV mobility on February 23rd; c: H4_{EV}'s on February 12th; d: example of visualisation's keys.

We used automatically recorded data from the home charging station and Carwings EV information system to augment the visualisation. Light blue circular areas represent time periods when the EV was plugged in at home but not charging (e.g. **Figure 7-6c**, around 6-8A.M.) while dark blue circular areas indicates time periods when the EV was charging at home (e.g. **Figure 7-6c**, around 2-4A.M.). Following the same colour code, light and dark blue areas on the edge of the clock represent charging events *away* from home (e.g. **Figure 7-6b**, around 2P.M.). We indicate the battery's state of charge at the beginning and the end of each charging period and after longish journeys. **Figure 7-6d** presents an example of visualisation's keys, personalised for each participant.

7.4 REFLECTING WITH PARTICIPANTS ON E-MOBILITY BEHAVIOURS

We conducted interviews with each participating household, in which we used the visualisations to help participants reflect on what they did during each day, how and why they used their EV, when, where and why they charged it, and issues going on in their lives at home or at work that might affect their mobility needs. Each interview lasted about 45 minutes and took place at the participants' home or workplace, with one or two household members. Each session was voice recorded and transcribed. We briefly introduced the visualisation to the participants through an enlarged and generic mobility clock. The actual interviews were conducted using an A3 paper sheet with seven mobility clocks representing the last week of driving and charging behaviour from before the interview date. **Figure 7-7b** illustrates this setting.

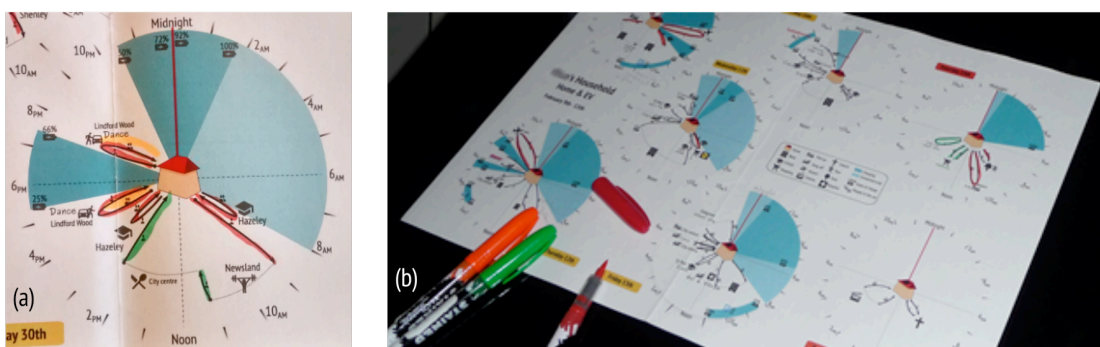


Figure 7-7 Interviews pictures. a: H1EV's highlighted trips on February 30th; b: H4EV's full week visualisation

We initiated the discussion by asking them to talk us through their patterns of EV usage as shown in the mobility clocks. During the interviews we asked open questions such as ‘*How did you plan this trip?*’ and ‘*Why did you decide to undertake this journey?*’, as well as closed questions such as ‘*Was this charging event planned or opportunistic?*’. We also invited participants to use different coloured pens to indicate flexibility of trips

(**Figure 7-7a**). Red indicates inflexible trips that had to take place at the time when they took place (for example a school run) and green indicates flexible trips which the participants could have undertaken earlier or later than they actually took place. In other words, a flexible trip is one that could be time-shifted (started earlier or later), while an inflexible trip has to start at or near the time when it did.

The participants had no difficulty interpreting the mobility clocks and describing their daily routines. The only difficulty was changing from one day to the next as it required a mental exercise to visualise the end of the day on one mobility clock and the start of the next day on the following mobility clock. In our experience, the use of behaviour visualisations led to deeper insights and more engagement than traditional unmediated interviews. Participants uncovered their own routines, made new discoveries about their own behaviour, explained their behaviours or reasoning at the time with anecdotes triggered by events or situations recorded in the visualisations and occasionally checked their dairies to add vital information that was missing from the visualisations.

7.4.1 DAILY USAGE

For all participating households, the EV is the primary car and is used for any local trip and daily commute. Many had either a second car or a bicycle as backup. H4_{EV} and H7_{EV} used the EV for all trips, even those that stretch beyond the nominal range, while H1_{EV} and H6_{EV} used a fossil fuel car for out-of-town trips. H4_{EV}, H5_{EV} and H7_{EV} had jobs and used their cars for daily commutes to and from work. These trips were obligatory and not flexible. However H1_{EV}, a retired couple with children, indicated similar constraints as they engage in many activities (e.g. visits to the yoga class, doctor's appointments) as well as school runs and children activities.

Figure 7-7a shows H1_{EV}'s non-flexible trips in red: a school run and a yoga class in Newland in the morning marked. The rest of the sport session did not have a time constraint, marking in green the way back and lunch break in the city centre as more flexible activities. Overall participants marked between 25% and 40% of all trips as flexible and 50% as non-flexible. We note that participants did not mark all trips. Most of the non-flexible EV activities were connected with appointments, classes or meetings.

Several participants remarked that during actual driving there is also some flexibility as they are able to adjust their driving behaviour when noticing that electricity consumption deviates from what they had planned for. On such occasions they are able to consume less power by driving at lower speed or switching off heating. A

different point was made by the husband in H3_{EV} who drives mostly for very short trips, and never risks pushing the available mileage (as indicated on the EV mileage prediction indicator) to its limits. They noticed a perverse effect of driving only short trips: the range – computed on past driving habits – becomes shorter and shorter and their willingness to drive for longer distances also decreases. Improving the range prediction with a forward view of the household's upcoming trips appears to be an important step towards an easier trip planning.

7.4.2 PLANNING

Family life in most of the households requires coordination and management of mobility needs of both parents and children. Most trips are regular and fixed, e.g. school runs of the children, and are incorporated into planning of weekly schedules to make sure that the car is charged with sufficient energy for these trips. Planning is essential for the participants to anticipate the use of their cars.

Participants mention a continuous awareness of the state of charge of the car's battery and how this determines the remaining range. We observed two forms of planning, either in a weak or strong form depending on how much routine behaviour is involved in a trip. For instance, daily mobility routines require no explicit form of planning; the participants have learned the driving implications from previous trips. H4_{EV}'s husband has distance and energy demands memorised for all routine trips. Yet even for routine trips participants estimate the electricity demand beforehand.

■ H1_{EV} (husband): *'It's easy to do in your head (daily trip planning), because there are only 3 or 4 distances.'*

In contrast, exceptions to daily routines require more planning effort. H3_{ev} makes use of a calendar in the kitchen to indicate unusual events for the whole family. This helps him to anticipate any need for special EV trips. In H4_{ev} the husband has a similar calendar on his smartphone of which he makes use to plan the coming EV usage. He would appreciate if the car could be aware of upcoming events automatically.

On top of the household's activities, the season and weather impacts on the way participants use their EV. In the summer there are more opportunities for alternative modes of non-motorised mobility such as walking or cycling. When there is good weather H4_{EV} often does not use the EV as part of a conscious decision to increase the households' level of physical activity. Looking at H7_{EV}'s data we were surprised by the radical changes in the charging pattern from one week to another. During the interview we understood that while H7_{EV}

normally relies on free public charging, cold winter nights alter the charging pattern. To defrost the car's windscreens, they decided to have the car at home as they can then use a smartphone app to start the heating while the car is charging in the driveway. This highlights that even regular routines can be altered to satisfy a different objective, for instance from cost saving to comfort.

7.4.3 ROLES OF EV USERS

The management of EV charging is mostly done by one person in the household – usually the person with the interest in energy and car technology and often the one who has driven the EV purchase decision. However, the usage of the EV is more evenly spread across all the drivers in the household. In H1_{EV}, the husband is doing all the planning of charging management while his wife uses the EV as a normal car without looking at its state of charge.

■ H1_{EV} (husband): *'My wife is not aware of it (state of charge), she just drives it.'*

Similarly, in H7 the EV is mostly used by the husband. Occasionally his wife drives the EV, particularly if she is late for work as there is reserved parking for EVs near her workplace. Sometimes, their daughter wants to be picked up with her friends and show off the EV but other than that the husband is the household's main EV user.

7.4.4 PLUG-IN AND CHARGING ACTIVITIES

For many households plugging in the EV and starting a charge has become a routine activity which is executed at a particular time of the day and in a particular way. H1_{EV} plugs in the EV every evening before going to bed. This has been integrated into the evening routines of H1_{EV}'s husband which includes locking the door, turning off the lights, and connecting the car to domestic charging station in order to start the charge.

While H7_{EV} connects its EV in the evening, charging is scheduled not to start until night. H7_{EV} had originally planned to adopt the Economy 7 tariff – but this plan never went ahead and he now still works through a routine for charging which is not applicable at his house. H4_{EV} is on Economy 7 and has configured charging to start after midnight. This only works if the EV is connected, but sometimes H4_{EV}'s husband forgets to plug in his EV after coming home. As a result, the EV has not been charged overnight.

We observed that the more participants used their EV, the more they plugged it in all the time, either at home or at work. This correlation seems obvious as there is a higher need for energy. As a result, households H2_{EV}

and H4_{EV} (Figure 7-6b and c p.141) connect their EV almost each time they are not driving, creating opportunities for controlling when precisely to start the charging process. In contrast, H6_{EV} only plugs in the EV when it is needed and hence there is reduced opportunity to fine-tune the timings for charging. In the case of H6_{EV}, it is hard to establish a link between PV and EV.

The confidence of users in EV technology has implications for their charging preferences and behaviours. While driving an EV does not create any problems, charging EVs is a big issue for the participants. Most participants see the home as a more predictable and reliable charging facility in contrast to public charging points. Although H7_{EV}'s husband usually prefers free public charging networks to save money, he often resorts to charging his car at home on Saturdays. This is because public charging points such as the ones at IKEA or at the Nissan dealer are likely to be busy on weekends. In H4_{EV} the husband charges mostly at home as he can cover all of his daily trips with one full charge. Sometimes he charges at work but there is not always a parking bay available if all spaces are occupied by other EV drivers.

H4_{EV} (husband): 'It's wasn't crucial (charging at home) [...] I knew I'll be running around here (driving later on in the day) [...] but I didn't know if I will get a charging position at work.'

In contrast, H5_{EV}'s lady shows high confidence in her workplace charging station. Charging only the minimum required amount to get to work, she arrives almost empty at work to take advantage of the free charging. Even though it can appear as an audacious behaviour, this confidence came from daily commutes and the insurance of being able to charge. This does not apply to H5_{EV}'s other trips which are rare and within a comfortable range.

7.4.5 FREE PUBLIC CHARGING AS A REPLACEMENT FOR HOME CHARGING

While home charging is seen as the most reliable option, public charging points can replace home chargers if certain conditions are met. H7_{EV} mostly charges at IKEA which is currently free.

H7_{EV} (husband): 'I charged at IKEA [...] that is within walking distance from home.'

While H7_{EV}'s daily routines are driven by the desire to save money and fast top up from the free rapid chargers, it is only the close distance from home that makes it a real alternative. The IKEA public charger has effectively become the (alternative) home charger as it is only a few hundred meters away from H7_{EV}'s house which causes the boundaries between private and public charging to blur in this specific case. H7_{EV} also

changed its shopping preferences to fit with this new routine, using a supermarket that is close to the free public charging point in order to charge and shop at the same time.

While some households like H7_{EV} exhibit clear choices about where to charge and their mental reasoning behind it, others appeared to become aware of some potential choices during our interviews. For instance, H3_{EV} charges only at home, not bothering with calculations about charging at a nearby rapid station which might be cheaper than charging at home. However, while describing his daily routines based on our visualisations, he outlined the need for a tool that would compare the potential charging points in the neighbourhood (including charging at home) in terms of tariffs and other benefits or constraints. In contrast, H4_{EV}'s husband changed his mind and do not bother looking for free charging station when he can charge at home.

H4_{EV} (husband): 'Do you realise that the actual savings between paying for charging at home and using the 'free' public charging is only saving 50p to £1 on average? I discovered that going to the trouble to use the 'free' charging was often more effort than it was worth!'

7.4.6 EV AND SOLAR PV CONNECTION

The combination of solar PV and EV is of great interest to all participants. Even those participants who have an EV but no solar PV installation have considered investing in solar. They are hesitating to invest into solar PV mainly because of the change of UK government policies in reduced subsidies for solar PV installations and the cut in Feed-in Tariff which has a negative impact on the expected payback period.

In H6_{EV}, the husband is sceptical about the notion of self-sufficient electric mobility, maintaining that there is no direct link between PV and EV. However, he does admit being interested in real-time information about how much power from the PV would go into the EV *'if such a link had existed'*.

As the most active of the participants, H5_{EV}'s members are away at work during weekdays. However, they look at the weather on Friday evening to see if it makes sense to wait and charge from the sun on Saturday or Sunday, of course provided it fits in with their plans for the weekend. At first motivated by the money, they explain how they realised the potential for other benefits.

EV is potentially in conflict with other household appliances which can also take advantage of solar energy. For instance, in H6 the husband does not really care whether the local generation powers his car or his dishwasher. However, the participants point to barriers which make the exploitation of solar energy for EV charging

appear difficult. In H1_{EV} the husband has observed that the EV charger requires a constant high power which exceeds the peak capacity of his solar PV installations so that always less than 50% of the charging energy can be provided through solar even on sunny days.

Our four participating households with solar PV installed their PV before getting the EV. All but H6_{EV} were keen to try out the EV in combination with their solar PV while H6_{EV} sees the solar PV as a ‘separate’ system. For the others, solar PV created an awareness of energy savings which has strengthened their motivation to purchase an EV. The idea of driving an EV through solar energy is an effective use of locally generated surplus electricity. If in addition the Economy 7 tariff is available, some participants argue that this guarantees constant cheap or free energy supply around the clock with maximum flexibility about when to start a charge. However, for others this creates a complex decision space and they struggle to calculate whether it is better to use cheap night-time electricity or green solar energy during the day. To support their decision making they identify the need for information currently not available: primarily real-time information about the grid’s electricity mix and the flow of solar energy into the car batteries.

7.5 UNDERSTANDING BEHAVIOURS

Through our EV study we revealed numerous issues which impact on the feasibility of achieving self-reliant mobility. On the one hand, quantitative data analysis illustrated a great potential for using solar PV to power EVs with sufficient electricity to cover a large fraction of the daily mobility and electricity demand. On the other hand, our diary study and Participatory Data Analysis has shown barriers but also opportunities for effective EV solar charging practices.

7.5.1 VIABILITY OF POWERING EVs WITH DOMESTIC SOLAR ELECTRICITY

The EV and solar households in our study currently use only a limited fraction of solar electricity for EV charging (ranging from 1% to 25%). However, on a significant number of days households do indeed generate enough electricity to cover their EV electricity demand. For some households the number of energy-positive days makes up even for the majority of all days and is as high as 79%. An increase of solar PV capacity in combination with installation of a home battery solution to bridge the time difference between generation and demand could make self-sufficient electric mobility a reality, albeit at a significant investment cost of several thousands of UK pounds. Alternatively, households could adjust their mobility and charging behaviour to

more effectively use self-generated electricity, for example by time-shifting non-essential journeys. An obvious drawback of powering the EV with solar electricity is the electricity cannot be used in the home (as it currently is). However, the emotional benefits of being able to completely power their EV with free, green, self-generated electricity could be a big driver for households to adopt this option and a motivator for behaviour change.

7.5.2 FLEXIBILITY OF MOBILITY DEMAND IN TIME AND SPACE

In the home, energy related behaviour change is connected with the use of appliances. With respect to EVs, energy related behaviour change is connected to mobility. Not using the lights to save energy might be inconvenient, not being able to drive feels like a much more difficult limitation. The desire to use a car is not just a matter of utility (e.g. having to go to work) but is closely connected to notions of autonomy and freedom (perhaps more so in the US than in Europe and Asia). Cars and mobility are powerful emotional triggers and thus the proposition to curtail or shift mobility is a difficult one. It was therefore surprising to see that participants seemed open to the suggestion to change their behaviour. While mobility curtailment seems difficult, the option to time-shift trips to an energetically more optimal time seems doable – except that currently EV drivers do not have access to the information that would allow them to make effective decisions.

7.5.3 IMPLICATIONS: TOWARDS SUPPORTIVE TOOLS

Beyond understanding the context of EV and solar households, the key objective is to determine which technological interventions might make sense in this context. We argue that ubiquitous computing technology can play a major role in dissolving the tensions between potentials and barriers for self-sufficient mobility. EV drivers lack tools that are informed by and address the needs of the rich social patchwork of EV and solar households. Current technological interventions are narrowly focused on the driver's experience and rooted in the perceived limitations of EVs.

Throughout this thesis we used the local generation to motivate the research and we emphasised that householders are proud of producing their own electricity and most of them try to maximise their self-consumption. While the generation is right on top of the roof, the connection between EV and PV and more generally between domestic consumption and generation – either local or from the grid – remains hidden. Participants make the link between supply and demand overall, but not on a daily basis. EV drivers currently have no understanding or awareness of the energy mix in their cars' batteries. How much electricity came

from green sources and how much came from dirty sources? This issue goes beyond solar PV and EV householders, as the energy mix in households without solar PV is even more opaque. Introduced at very early stage of this research project in study A, the battery metaphor showing green energy availability for the washing machine seemed difficult to understand. However, our simulation was rather simplistic. In the EV context, the battery goes beyond the metaphor, with an actual battery in the car. We believe that displaying a battery that indicates how much green and dirty electricity is ‘stored’ in the battery could raise awareness of the electricity source. A more elaborate version could differentiate between free, cheap and expensive electricity. A virtual fuel mix indicator could become a powerful tool to stir behaviour change and help EV households stay within their green electricity limit.

Current information interfaces are vehicle centric and they have no understanding of the user’s and household’s context or past and future behaviours. For example, we reported $H3_{ev}$ describing the spiral down: the less you drive, the less autonomy is predicted by the car, reducing the driver’s confidence. There is an opportunity to build predictive tools for EV drivers that can anticipate future mobility demand, providing charging mechanisms that understand contextual EV usage patterns and recommend energy management strategies. A predictive tool could reduce cognitive load and mental stress incurred by EV drivers to achieve their personal energy goals while providing smarter charging decisions.

Through this study we realised that most EV participating household were struggling to alter their everyday routines at the beginning, without even thinking about charging with green electricity. However, local generation and EVs give rise to very similar difficulties and behaviours related to collaborative and proactive planning. For instance, EVs are shared within a family and serve multiple purposes involving various stakeholders. Improved utility resulting from better planning could reduce coordination overhead and might accelerate adoption of EVs. Such supportive digital tool would be compatible and could embedded Demand-Shifting decisions.

7.6 REFLECTION ON PARTICIPATORY DATA ANALYSIS

In this study we implemented the Participatory Data Analysis (PDA) for the second time. Through this method we took the opportunity to double check our observations of energy and mobility data points. Participants’ analyses complemented our interpretation of the data. In contrast with the first implementation,

we did not provide a ‘Potential’ visualisation, but rather we focused on the actual data. Showing participants what they could have achieved had been particularly powerful around the washing machine to observe their reaction and comment. However, all the EV participants were not equipped with solar PV, limiting such shifting analysis.

In contrast, we were able to build a much more personal view of the EV routines thanks to rich qualitative data from the trip diaries. The combination of manual and automatic records with participants’ comments from the trip diary provided rich pictures of their mobility. Some participants told us they had difficulty engaging and filling in the trip diaries. However, when they looked at the visualisation they told us they could have been more involved and it would have created an even richer picture. We only engaged one household member in the interview, but we steered the discussions towards only focusing on home charging, as opposed to including public and work charging. This is a way to keep control of the discussion without verbal interventions. The discussion was set explicitly around the households.

Taking into account lessons learned during our first PDA, this second implementation relied on data from the one or two weeks right before the interview. The data was fresh in participant’s mind, thus generating more effective discussions. The timeline of our study was also different as we ran the PDA before designing interventions or recommendations. This was much more effective in generating design ideas than generic pictures presented during the exploratory interviews. The combination of the logs, diaries and visualisation gave us the opportunity to fully understand the context to provide carefully designed recommendations.

7.7 CHAPTER SUMMARY: DEMAND-SHIFTING AMONG OTHER NEEDS FOR SUPPORT

In this chapter, we explored EV routines broadly then narrowly through the domestic lens, highlighting a gap in the literature: the EV as a new form of home electricity consumption and its connection with domestic micro-generation. We provided a quantitative and qualitative analysis of this context.

Our exploration identified an opportunity: most of the participants are confident in their EV and its charging at home. This contrasts with the existing literature focusing on range anxiety and public charging. There is a research gap around the EV as a new form of home electricity consumption. Furthermore, we highlighted that the link between EVs and domestic micro-generation relies on the desire to be self-sufficient. This objective relies on the same requirements as minimising the environmental impact. The quantitative analysis gave a glimpse of the opportunity for self-sufficiency with PV generation and EV consumption of similar magnitude,

though, a closer look to the data emphasised only a very limited fraction of the solar PV outcome was going into the EV when charging at home.

We echoed our previous findings. Targeting mobility routines enlarges the energy audience. While there is technically plenty of room for improvement by shifting the EV charging time, we still highlighted that there are few opportunities for time flexibility. We confirmed the already complex and dynamic picture of the domestic routines started with the washing machine. While the washing machine was well-known and did not require any support, we emphasised the need for supporting EV mobility at home. This brings the opportunity of blending support for Demand-Shifting directly into general support for EV mobility. As mentioned in the conclusion of study C, we did not deploy in-the-wild interventions to support Demand-Shifting. However, we proposed an agenda for further investigation into increasing the visibility of green energy, personalised energy management and supporting EV routines. In the next chapter we build on our conclusion from studies A, B, C and D to formalise and design an interactive Demand-Shifting system.

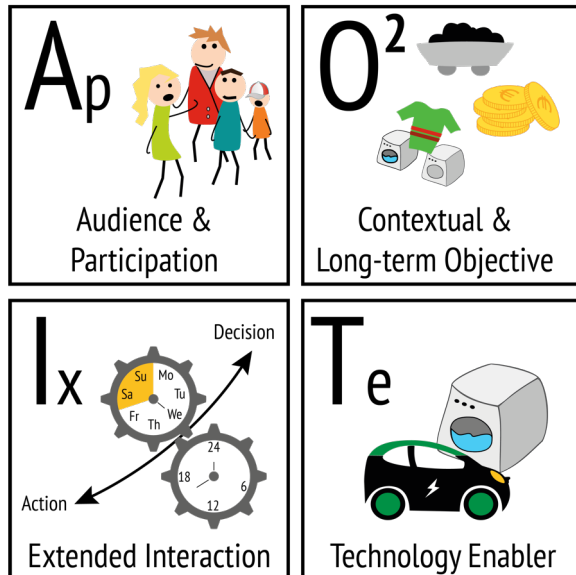


Figure 8-1 Four key elements to frame the outcome of this thesis.

8

Digital Conversation

A Conceptual Framework for
Interactive Demand-Shifting

*‘Engineers are all basically high-functioning autistics
who have no idea how normal people do stuff.’*

CORY DOCTOROW, EASTERN STANDARD TRIBE, 2004

We dedicated this thesis to the understanding of how householders who have solar PV on their roof do ‘stuff’. In order to make our findings intelligible, we aim to organise them into a conceptual framework. In this chapter we first motivate the need for a conceptual framework. Second, we combine the results of our four studies to define four key elements: audience and participation, technology enablers, long-term and contextual objectives and time and purpose of interaction. We illustrate these four elements in **Figure 8-1**. Third, we organise these elements into a ‘Digital Conversation’. Finally, we present a concrete example of design relying on the Digital Conversation.

8.1 CONCEPTUAL FRAMEWORK

Each of the chapters 4 to 7 presented insights and discussions from empirical studies, offering room for the reader to think about their validity and implication for the design of domestic energy systems. However, we believe it is important to share the vision we built from these studies in order to draft the potential future research directions of the field. To this end we propose a conceptual framework.

In this thesis we use the term conceptual framework as the definition of key concepts organised into an abstract and logical structure. This format provides the right balance between freedom of interpretation and guidance where other formats, such as mental models or tools, would have a very specific lens. For instance, building a mental model of our participants’ energy behaviour and strategies of how they deal with Demand-

Shifting could be a form of sharing our interpretation. However, this model would be closely tied to the behaviour of our participants. Designs or tools would be another way to communicate our findings through a concrete implementation of a domestic energy management system with Demand-Shifting mechanism. We have built and initiated several digital tools throughout this research project in order to analyse data, simulate scenarios, intervene in the wild and try out software architectures. However, we believe it is more relevant to report on the implications and challenges emphasized by this research.

Thus, through this conceptual framework we aim to provide our understanding of the domestic solar generation context by formalising and organising the key outcomes. We motivate and define each concept, highlighting the implication and potential challenges. As a transdisciplinary research, we believe this step is important to communicate our findings. For instance, the designers could extract clues for further developments and redesigns of domestic technologies. In the last section we present a concrete example of a Digital Conversation to support an interactive Demand-Shifting mechanism. We aim to show how our conceptual framework can be used in the design and development of an interactive system. In the engineering communities, this example can serve as an application case to address underlying challenges.

8.2 FOUR KEY INGREDIENTS FOR DOMESTIC ENERGY MANAGEMENT

In this section, we conduct a discussion on the findings from the user studies A, B, C and D with the literature to motivate and define the four key elements of our conceptual framework. First, we define **long term and contextual objectives** reflecting the householders' aims. Second, we **extend interactions** in time and purpose, offering more opportunities and flexibility for householders to collaborate and negotiate with the home. Third, we **enlarge the participation** for a more effective interaction. Finally, we define a **appliance taxonomy** that allows flexible controls, supporting negotiation and collaboration and depending on household, time and objectives.

8.2.1 EMERGING ENERGY BEHAVIOURS

The initial motivations of the thesis build on the early evidence that emerging energy technologies create, alter or disrupt behaviours (Keirstead, 2007; Dobbyn & Thomas, 2005; Hondo & Baba, 2009). Through engagement, objectives and time, we highlight the challenges arising to support these emerging energy behaviours.

Engagement

In our studies we corroborate the evidence from these early works (Keirstead, 2007; Dobbyn & Thomas, 2005; Hondo & Baba, 2009). Most of our participants with solar PV naturally engage in actions to increase the use of electricity they produce locally. Participants were engaging with particular activities or appliances, because they were giving them more value (e.g. H12_{WM} was using the slow cooker almost on a daily basis) or because it was natural and easy for them to do that (e.g. H14_{WM} was shifting the washing machine because the wife was working at home).

We identified that there is a wide range of motivations for people to engage in consuming local electricity. In the UK, there is a financial interest in consuming local electricity. The environmental impact was also a motivation for the participants. However, both financial and environmental motivation play a more important role in *installing* solar PV than managing local electricity on a daily basis. For the participants who engaged on a daily basis, the strong motivation was being proud of consuming their own electricity and aspiring to being self-sufficient.

Even if people are very strongly motivated, consuming local electricity is a challenging and time-consuming task. It requires combining multiple sources of information including current generation, weather forecast and knowledge about forthcoming household activities. Part of this information is difficult to access, not very accurate, and activities are not always planned in advance. Some participants report they thought about engaging in a specific action but they were missing either information or automation. The need for appropriate information and support was clear, although we also found that there is a thin line between supporting behaviour and reducing engagement. It is important to keep the user as part of the decision process.

Objectives

The objectives we consider to be what drives the householder's decisions and are influenced by the motivations described in the previous section and the contextual situation. As highlighted by Crabtree and Rodden (Crabtree & Rodden, 2004), there is a fundamental difference between the home and the workplace: the home is not driven by productivity. Concepts of production and efficiency in domestic life cannot be adequately described in formal terms of capital production. The home is not characterised by a common orientation towards a shared work objective but is characterised by multiple objectives depending on the context and the residents. Thus, a 'best' solution is a compromise balancing a set of objectives at a given time. In the long run participants are driven by their motivations, for example wanting to maximise their use of local

electricity generation, minimise their energy bill, minimise their environmental impact. These *long-term* objectives should take into account the micro and macro environment and deliver information on their calculation at different levels of detail that should be accessible on demand. On a daily basis, householder's objectives are closely tied to a specific period of time and the current situation. These *contextual* objectives are objectives that are tuned to the context. As suggested by Davidoff, the system should '*allow for the organic evolution of routines and plans*' (Davidoff, Lee, Yiu, Zimmerman, & Dey, 2006). Thus, objectives should also be able to change in accordance with any changing habits and routines that the householders may develop.

Ignoring long-term or contextual objectives can lead to unsustainable interaction between the system and the user. On the one hand, there are situations in which participants knew that they were going against the recommendation from the system but that this was deliberate – in some instances they weighed up various arguments and prioritised comfort rather than say, saving money. Receiving negative feedback in such situations led to comments from participants such as '*I don't want to feel guilty*' (H6_{WM} husband, Study B). On the other hand, it is important to support those who engage with Demand-Shifting. For example, one of our participants was commenting with emotion on a situation when she received a text message suggesting a 'better' time to run the washing machine: '*well I knew, this is why I ran the dishwasher at that time!*' (H14_{WM} wife, Study B). Another participant had scheduled his heat pumps to turn on at midday to catch solar electricity generation. These participants' comments reflect the limits of focusing on a single routine or appliance like we did with the washing machine, because participants will always be having to juggle a range of different appliances. However, it also enforces the need to support contextual objectives. It is not enough to target one long-term objective such as 'minimising the environmental impact'. This objective should be tuned for the specific context, leveraging elements (e.g. appliances, activities) that the householder is willing to engage with.

8.2.2 EXTENDING INTERACTIONS

The emerging engagements and objectives discussed in the previous section emphasize the need to extend the interaction in the home between householders and energy technologies. **Figure 8-2** presents examples of interactions (grey circles) in two dimensions: purposes (blue on the y-axis) and times (green on the x-axis). In this section we detail both dimensions.

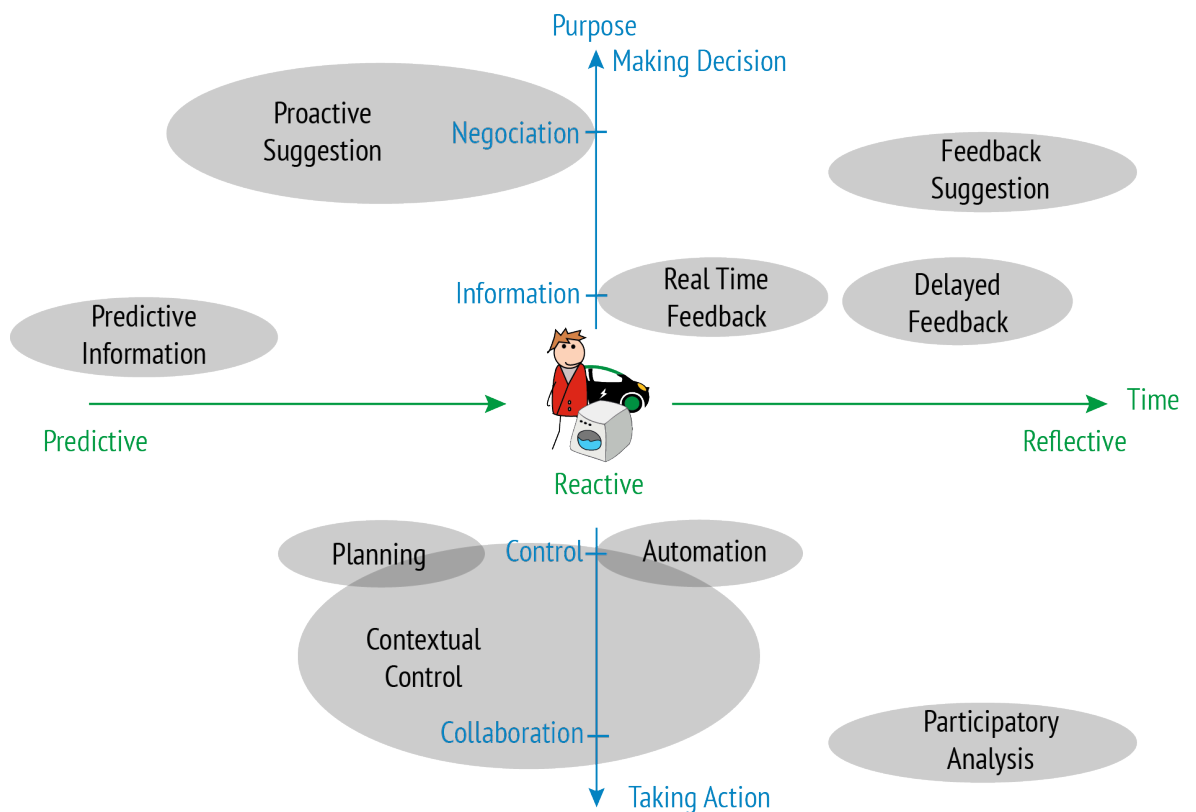


Figure 8-2 Purpose and time of interaction. Each grey circle represents an example of interaction, distributed in time (x-axis) and purpose (y-axis)

Extending the Type of Interactions

While current home energy management systems provide *information* through eco-feedback and *control* through manual or automated appliance's commands, these interactions are not enough to manage emerging energy technologies. The purpose of interaction between householders and the home is wider, towards decisions and actions. Beyond information and control, we formalize two additional purposes of interaction essential for domestic energy management: *negotiation* and *collaboration*.

- **Negotiation** – in many situations there are multiple objectives bringing different constraints and benefits. To find the best compromise, householders and the home should be able to negotiate and reach an agreement. In contrast with information, the negotiation is bidirectional, providing arguments (e.g. suggestions, solutions with cost and benefits) and responses (e.g. approval, alternatives, reject, non-response). **Figure 8-2** illustrates the negotiation on the y-axis, extending the purpose of interaction towards making decisions.
- **Collaboration** – householders do not intervene only in the decision process. They also need to take part of the action, for instance to get the washing machine ready or to plug in the EV. These are collaborative interactions with the home. A collaboration is an interaction allowing the home and the householders to extend the number of opportunities and their impact through a joined effort. **Figure 8-2** illustrates the collaboration on the y-axis, extending the purpose of interaction towards taking actions.

Times of Interaction

Most of the research into domestic energy management with users focuses on energy awareness and feedback (Davidoff, Lee, Yiu, Zimmerman, & Dey, 2006; Fischer, 2008). However, householders need to know in advance what their solar PV will produce and when, and learning from past events is really limited in the context of local generation.

In the Netherlands, Kobus and colleagues investigated how a washing machine that is able to wait for a sunny period impacts on the user (Kobus, Mugge, & Schoormans, 2013). They deployed an Energy Management System (EMS) 'Smart wash' in 24 households who had solar PV on their roofs. Householders were able to see the generation forecast over two days as feedforward and to set a deadline for their washing machine load to be done. The authors report that people tended to shift their washing to the peak solar generation period. They recommend the use of feedforward information, such as prediction, allowing the user to anticipate when the best time would be and an acknowledgment of the effort this involves.

Banerjee and colleagues looked at how home automation techniques could support householders increasing their use of local generation in a house that is not connected to the grid (Banerjee, Rollins, & Moran, 2011). They suggest three tools: (i) An early warning allowing the resident to anticipate a level of battery critically low, (ii) advice on the best time to execute high-power tasks (iii) and energy conservation suggestion such as refrigerator temperature. Similarly, Simm and colleague conducted a participatory design methodology to support the use of wind energy on the island of Tiree (Ferrario, et al., 2014; Simm, et al., 2015). Their findings highlight the need for energy forecasting: 'the likely future availability of energy'. Our studies also emphasised the need for interventions at multiple points in time around an energy event. Looking back to **Figure 8-2**, each example of interaction is distributed on the x-axis, through the time. It emphasises the need to expand the typical energy interventions happening after an event with new interventions before and during the event.

- **Predictive Information** – Weather forecast, local energy forecast or any information correlated with Demand-Shifting brought to the householder in advance can be valuable (See p.72, 100; (Banerjee, Rollins, & Moran, 2011));
- **Proactive suggestion** – High-level pro-active suggestions support decision-making in advance while giving householders the opportunity to ignore them (See p. 114; (Banerjee, Rollins, & Moran, 2011; Mennicken & Huang, 2012));

- **Automation** – Some participants want everything that can be automated to be optimised, e.g. the surplus of solar electricity used for hot water heater or heat pump (See p. 102);
- **Contextual Control** – Participants are keen to let the appliance manage the load by itself under a set of constraints such as deadlines (See p. 118). Sometimes they want information on how the decisions are made to evaluate if they can trust the automation.
- **Real-time feedback** – Sending a text message right after an event was useless in the washing machine case but it might be useful with the EV when plugging, unplugging or charging the car (See p. 112, 145).
- **Delayed feedback** – while the email sent after few days as a summary did not generate a lot of enthusiasm (See p. 111), the literature highlights evidence of benefits (Darby, 2006; Fischer, 2008).
- **Feedback Suggestion** – The high-level visualisations used for the PDA highlighted interest to see suggestions or high-level information over a longer term analysis, e.g. trends of best shifting, long-term benefits of solar PV (See p. 96).

8.2.3 WIDENING THE PARTICIPATION

The householder's motivations influence the objectives and the householder's activities make use of the appliances. While the householders' behaviour has an important impact on energy in the home, there is a very limited literature on widening the participation, i.e. making energy-related concerns accessible, useful and attractive for more people in the household.

A very targeted audience

As introduced in the literature chapter, Strengers (Strengers, 2014) discusses the direct transfer of energy management from energy utilities to the householders with the growing use of smart meters and local generation. She refers to the 'Resource Man' as 'the ideal of a data-driven, technology-savvy home energy manager who is interested in, and capable of making, efficient resource-management decisions'. In order to mitigate this effect and take more of the household's context into account, she stresses two directions of research to focus on:

- Supporting the 'mess' of householder's everyday life, looking into daily routines to have a sense of their concrete home environment.
- Designing for others to widen the energy audience, opening up energy household decision making to the rest of the householders.

Widening the audience via emerging forms of data

Ambient displays are an attempt to diversify energy feedback and enlarge the audience. This new form of feedback allows integrating energy-related concerns in everyday life. For example, the Power Aware Cord

makes the electricity visible by lighting a power cord (Gustafsson & Gyllenswärd, 2005). Broms and colleagues designed the energy clock providing the last hour's or day's worth of electricity consumption, an object that we can look at like a kitchen clock (Broms, et al., 2010). Both technologies make the concept of energy more visible to the resident. Wessman and colleagues go beyond the visual and energy consumption dimension. The Peacetime tree prototype use bird sounds and smells to notify a peak time of consumption (Wessman, Colombo, & Katzeff, 2015). In contrast with other approaches stressing high tariffs and consumption, this project aimed to convey the idea that it is time to relax, and that we can switch off our appliances to enjoy bird song – thus reducing consumption through a different type of motivation. We illustrated these projects in **Figure 2-9** p.30.

Widening the participation via domestic routines

Looking at energy management from an activity and routine perspective, we uncovered a second opportunity to widen the energy audience. Like other studies, we found that in most households there is one person who is pushing the energy agenda – with an interest in how to reduce the household's consumption and an interest in technologies to support this. However, the persons doing the laundry in the household or driving the electric vehicle are not necessarily the same as those managing the household's energy. Thus, designing a support for shifting the washing machine time of use involves household members who had previously not shown a particular interest in energy matters.

Kobus and colleague noted complementary results in their study of the Enexis 'Smart Wash'. Some household members were unable to become interested in the washing machine as a smart appliance with energy saving potential, as doing the washing was not part of their role in the home. Talking to the 'Resource Man' about laundry routines can be rather ineffective. Hence the social dynamics surrounding household routines and the division of labour within the home are issues that will impact on the success of new technological approaches to support the change of such routines.

In this section we provided the motivation for supporting interactive Demand-Shifting. In our approach to the Demand-Shifting Mechanism we give an important place to the user as part of the system. Our framework especially emphasises the need for a 'conversation' between the users and the system. Contrasting with the recent user-centred work in the domain, there is no work presenting a concrete user-in-the-loop approach in the area of home energy management. On the one hand, the literature expands on highly relevant system

performances but without much consideration for the householders (Barker, Mishra, Irwin, Shenoy, & Albrecht, 2012; Crespo Del Granado, Pang, & Wallace, 2014; Molderink, Bakker, Bosman, Hurink, & Smit, 2010). On the other hand, the focus is on user interaction, providing energy feedback (Darby, 2006; Fischer, 2008) to the use in order to increase energy awareness. It relies on the assumption that the user will 'close the loop' by reacting to this feedback through energy behaviour changes.

8.2.4 FORMALISING ACTIVITIES' INTERFACES

Electricity is only a resource. The consumption is the result of using appliances through activities. Thus, in order to address the overarching objective of optimising energy consumption we have to look at the technology enablers, the appliances, interface between activities and the energy consumption.

Talking about appliances

Through the user studies we observed the importance given to each appliance was highly variable between households. In study B we collated the appliances mentioned by each participant and we built a map of appliances considered as shiftable (the green tick) or non-shiftable (the red cross) (**Table 8-1**). An exclamation mark indicates that participants did not have the appliance but still felt able to talk about it. Finally, the question mark indicates that participants asked us (or themselves aloud) whether the appliance was shiftable or not. We ranked these appliances by the number of participants who mentioned them.

The washing machine, dishwasher and dryer are the most common devices that participants mentioned as shiftable. However, this topic was discussed in the context of interactive demand-shifting. The hot water heater and space heating seem to be good shiftable devices too. However, participants described Demand-Shifting as much more automatic for these kinds of devices. All the participants but one had gas space heating, the most important part of the energy bill. Although the solar panels cannot power the gas heating system, several participants described situations where they had or they could have implemented an electric heating system in the living room to complement the gas consumption when they have spare electricity generation (heating (sup) in **Table 8-1**). Three participants asked '*Could the refrigerator be shiftable?*'.

Table 8-1 Talking about shiftable appliances. This is a summary from discussions during the washing machine PDA (p.102). Note: the interviews of H15_{WM} and H18_{WM} (shaded columns) were less detailed because no visualisation was shown for technical reason.

	H1 _{WM}	H2 _{WM}	H3 _{WM}	H4 _{WM}	H5 _{WM}	H6 _{WM}	H7 _{WM}	H8 _{WM}	H9 _{WM}	H10 _{WM}	H11 _{WM}	H12 _{WM}	H13 _{WM}	H14 _{WM}	H15 _{WM}	H16 _{WM}	H17 _{WM}	H18 _{WM}
Washing Machine	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓
Dishwasher		✓	✓	✓	✓	✓	!	✓	✓	!	✓		!	✓	!	✓	✓	
Tumble Dryer		!				✓	!		✓	!	!	!	!	✓	!	✓	!	
Oven	✓			✗	✗	✗	✓			✗	✗			✗				
Hot water heater		✓			✓	✓					✓	✓	✓			✓		
Heating (sup)				✓	!	✓				?		✓						
Lawn mower	✓									✓								
Heat pump		✓																
Hoovering				✓			✓											
TV, media				✗			✗	✗		✗			✗				✗	
Electronics				✗			✓	✗		✗	✗	✓		✗			✗	
Hot tub					✓													
Heat Lamp				✗														
Fridge						?						?					?	
Lighting						✗								✗				
Ironing							✓											
Kettle							✓	✗										
Bread maker								✓				✓						
Shower								✗										

✓ Shiftable ✗ Non shiftable ! Do not have ? Shiftable, could it?

At the bottom of the table we find the appliances that participants rarely talked about. On one hand there are common appliances such as lighting or electric showers which participants did not imagine as shiftable appliances. On the other hand, there are more exotic appliances for which some participants described an entire Demand-Shifting protocol they are implementing themselves. These included the slow cooker, the bread maker and the heat pump. This highlighted increased engagement of householders for a specific appliance or activity they considered more important. Thus, to engage householders it is important to cover a large spectrum of appliances.

Appliance Taxonomy Relying on User Study

The participants' discussions suggested a series of directions to classify appliances. In Chapter 2 p.44 we presented the various appliance taxonomies existing in the literature. Allerding and colleagues distinguished **controllable** and **observable** devices (Allerding & Schmeck, 2011) with subdivisions for each of these groups. Soares and colleagues organised the appliances into **shiftable loads**, **interruptible loads** and **re-parameterizable loads** (Soares, Gomes, & Antunes, 2012). Finally, Zhu and colleagues presented classification with **non shiftable**, **time-shiftable** and **power-shiftable** (Zhu, Tang, Lambotharan, Chin, & Fan, 2012). These taxonomies provide fixed boundaries on which appliances the system can handle and rely on very limited user study if any. In these existing taxonomies, there is no clear distinction between actions that are technically unfeasible (e.g. reducing the power of the washing machine), actions which do not make any sense (e.g. starting the washing machine without clothes in the drum) and actions that the user does not

want (e.g. running the washing machine after 10PM). Furthermore, there is no flexibility for an appliance to be shiftable or not depending on the time of the day, or depending on the households.

One of the contributions of this thesis is a deeper analysis of the dimensions in which appliances can be classified as shown in **Table 8-2**. In contrast with the literature, we choose a different approach in two dimensions, following the extension of interaction purposes discussed in the previous sections.

Table 8-2 Appliance taxonomy based on user studies.

		Interruptible H I →	Reducible ↕	Shiftable ↔	Actions
Negotiable	Washing Machine	✓	C+	C+	
	Dishwasher	✗	C+	C+	
	Tumble Dryer	✗	C+	C+	
	Electric Vehicle	✓	✓	C+	
	Oven	✓	C+	C+	
	Fridge	✓	✗	✓	
	Hot Water Heater	✓	✓	✓	
Non-Negotiable	Electric Heating	✓	✓	✓	
	Air Conditioning	✓	✓	✓	
	Coffee Machine	✗	✗	C+	
	TV	✓	✗	C+	
	Lighting	✓	✓	✓	

Decisions No Control ✗ Auto. Control ✓ Control with collaboration C+

First, we focus on extending the interactions towards decisions. This requires to define whether an appliance's usage can be negotiated with the householders. We illustrate this dynamic in **Table 8-2** (y-axis). The list of appliances represents examples that could be part of the system. For instance, we can find 'lighting' and 'TV' at the bottom of the list. For our participants, decision around the control of these appliances were clearly non-negotiable. On the opposite direction, the washing machine at the top was considered as negotiable, i.e. most participants could open a discussion on using the washing machine at a different time. We represent this axis as a coloured gradient to emphasize its dynamic between participants and overtime.

Second, we want to extend interactions towards collaboration. This requires embedding the capability and the need of appliances into actions. We picked three potential actions while this list could be extended further:

- **Interruptible**, the appliance can be turned ON and OFF, PAUSED and RESUMED for a short period of time without impacting the quality of its service. This implies that we need to define how long this period can be.
- **Reducible**, the appliance can be reconfigured or can handle dynamically a variable power rate, though, increasing the period of time required to deliver an equivalent service. This implies that we need a definition of how much this reduction can be.
- **Shiftable**, the service delivered by the appliance is postponed or anticipated.

We represent this dimension in **Table 8-2** (x-axis), as a series of action towards collaboration. For each appliance we categorize the action as:

- No control: Technical limitations or constraints do not allow this action;
- Automatic control: The action can be performed automatically, without user intervention;
- Control with collaboration: The action can be performed through a collaboration with the user.

Similarly to the negotiation axis, we use examples to fill in the table but other options could be selected depending on the specific appliance. For instance, the washing machine we used could be interrupted for a time, without the whole cycle. Some other washing machine might not support this action. By selecting a different, less intensive washing cycle, the consumption can be reduced. However, this action requires collaboration with the user. It is not possible to interrupt the coffee machine, but its use could be shifted in time in collaboration with the users.

The list of appliances considered in the system is variable from one house to another and will evolve over time. The list of actions could also be extended beyond interruptible, reducible and shiftable with more complex ones such as 're-parametrizable' as suggested by Soares and colleagues (Soares, Gomes, & Antunes, 2012). Note that our list of appliances is more diverse and considers a number of appliances not discussed in the approaches by Allerdig, Soares and Zhu. Particularly noticeable is the EV, an appliance that is not normally considered as a household appliance. The study in Chapter 7 is the first of its kind to consider whether EV can be considered a shiftable device or not.

8.2.5 ORGANISING FOUR KEY ELEMENTS

In this section we describe four key elements extracted from our user studies: audience and participation, technology enablers, long-term and contextual objectives and extended interactions. **Figure 8-3** illustrates the organisation of these elements, with the interactions in the centre, extended both in time and purposes.

On the left side, technologies serve the activities relying on defined characteristics of negotiation and collaboration. On the right side, motivations translate into a dynamic set of contextual and long-term objectives. On top, householders converse with the home. In the next section we formalize this view into a conceptual framework of Digital Conversation.

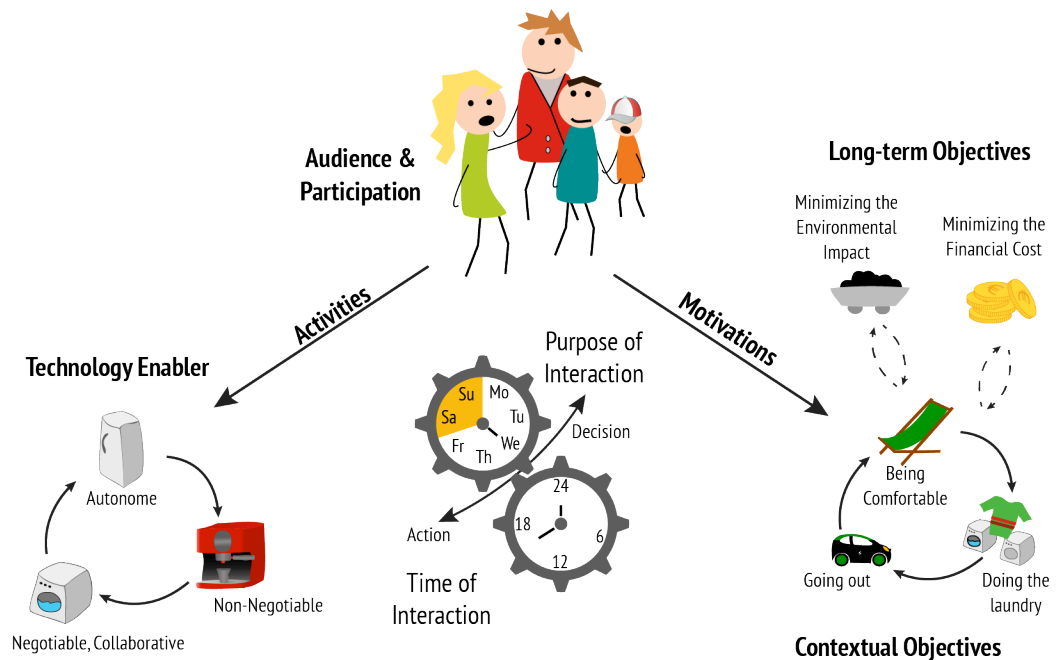


Figure 8-3 Digital Conversation framework. The interplay between audience and participation, technology enablers, long-term and contextual objectives and time and purpose of interaction

8.3 DIGITAL CONVERSATION

Mixing negotiation, collaboration and suggestion, the qualities described in the previous sections can be mapped to human conversation. In fact, a conversation is informal and spontaneous. While we inform and acknowledge, we can also argue and negotiate to make choices and decisions, or we can collaborate to take actions. In this section we introduce the Digital Conversation to translate our key concepts into implications and challenges.

8.3.1 REFLECTING ON AN IDEAL CONVERSATION

If we had to condense the general householder sentiment into two sentences, we would use the following:

‘Just do it for me or give me suggestions if you can’t. However, I might change my mind and do whatever I want.’

These two sentences capture the notion that under certain constraints householders prefer giving control of the appliance to a system. For instance, the washing machine and its contextual control can adapt the washing load to match the solar electricity generation but it has to be finished by a specified deadline. Otherwise,

proactive suggestions may notify a potential action to the user that would lead to an improvement. In both cases, the users can decide to change their plan by interrupting or forcing the start of an appliance. A typical conversation between users, appliances and a system to support the control between various components could look as follows:

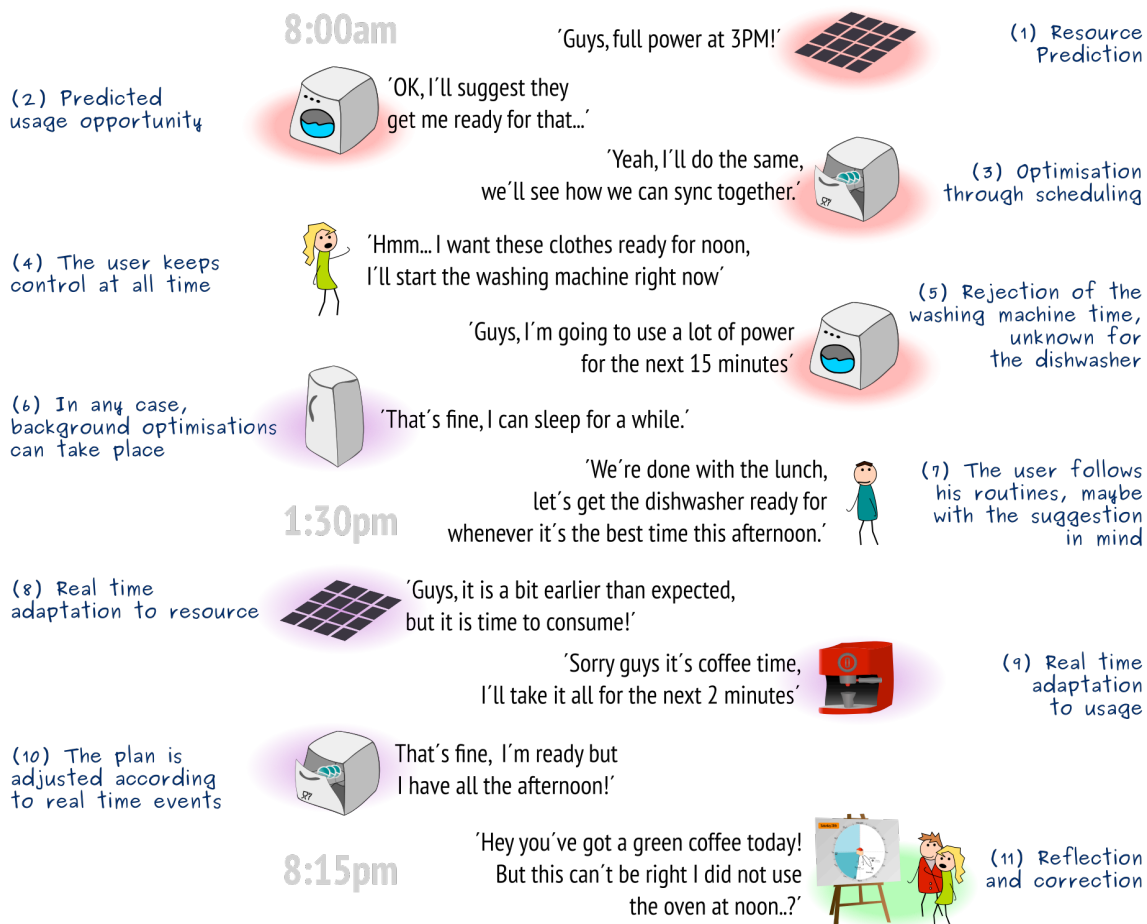


Figure 8-4 Conversation in the context of interactive Demand-Shifting.

Figure 8-4 illustrates an example of conversation that could take place between users and elements of the system in the context of an interactive Demand-Shifting. In this conversation we can observe three groups of features:

- Predictive elements (red) to anticipate situations by looking for optimisations, conversing with users and planning actions in advance. In the example, there is a prediction (1) of solar power generation (resource). Then, the washing machine and dishwasher are predicted to be used and an optimisation (scheduling of the best time of use) is suggested to the user (2, 3). The user rejects the washing machine suggestion (4). The system does not know the user response for the dishwasher yet (5).
- Reactive elements (purple) to deal with real-time situations and unpredicted events by looking for optimisations, conversing with users and executing actions. In the example, the system reacts to the

washing machine start. While it does not follow the best plan, other optimisations can be performed in reaction. The refrigerator will turn off for the short period of time that the washing machine is heating the water (6). Later in the day, the user gets the dishwasher ready to be run in the afternoon. This action could be a consideration of the suggestion provided earlier or it could be simply part of the user's routine (7). The solar generation (8) happen earlier than predicted (resource) and the coffee machine (9) is turned ON as an unpredicted event (usage). The system reacts by postponing the start of the dishwasher (10).

- Reflective element (green) to reflect on the past events and shares correction, evaluation and suggestions with the users. The example emphasises such reflections through a conversation between users at the end of the day (11).

Expanding on previous **Figure 8-2** p.157, which showed just the user side of the interaction, **Figure 8-5** now shows examples of features that the system could provide to serve the interactions as prediction, reaction or reflection. Each feature of the conversation implies its own challenges and research area, as presented in the literature through the ingredients of the Demand-Shifting mechanism (§2.4 p.38). We focus on the integration of these technologies altogether, focusing on the challenges of interaction between users and elements of the system as well as the consistency of information and actions throughout the conversation. We propose a 'Digital Conversation' to establish a consistent interaction between the user and the system's elements.

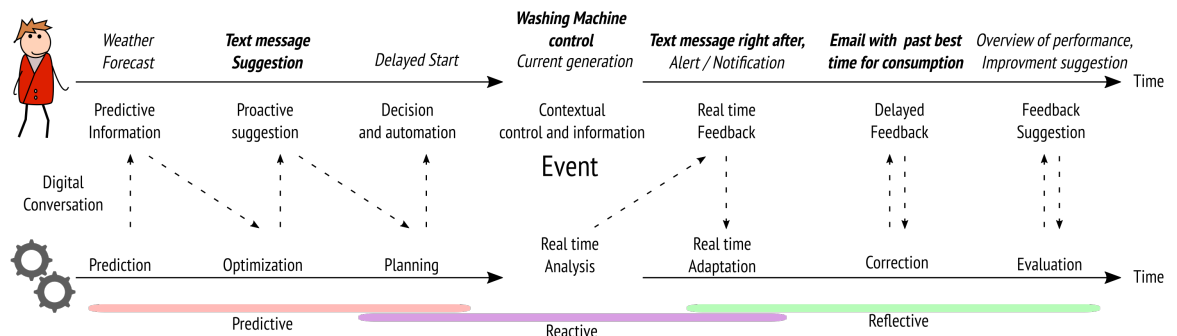


Figure 8-5 Digital Conversation to support interaction between user and elements of the system.

Figure 8-5 illustrates the digital conversation in the middle, as a dual communication. The system can inform the user in advance with prediction while the user can provide preferences and constraints (short-term objectives). The system can look for potential optimisations and provides suggestions. The user can agree or disagree, he can reply or ignore, he can follow what he agreed or change his mind. Dealing with uncertainty, the system defines the most probable plan and updates it on the go. However, any suggested information should remain valid till it has expired. The proactive suggestion is a key feature of the interactive Demand-Shifting, and in the next sections we focus on the main challenge of these suggestions: consistency.

8.3.2 IMPLICATIONS AND CHALLENGES

The implementation of a digital conversation has a series of challenges. In this section we emphasize them, raising research questions requiring further investigations.

The first challenge relates to the user. To support the digital conversation, digital tools should engage with the users beyond the typical user-in-the-loop. Householders should not be considered as a sensor who can bring only an additional data point such as a ‘satisfaction’ indicator. Including the users in the loop means allowing them to negotiate decisions and engage in collaborative actions. However, engaging with the user brings a set of challenges. The home has to take a temporary decision while waiting for a householder’s response that may or may not come. What are the best subsidiary decision? How do parts of the home collaborate towards the best solution when the householders change their mind? Which strategy to adopt when suggested actions had become irrelevant because of, for example, a weather change? How do we moderate the interaction, adapting the number and type of exchange to each householder?

A Digital Conversation should be able to combine seamlessly past, current and future data. For example, we sent reactive text messages and controlled the washing machine in real time. These interventions required combining collected data about the past hours with predicted data about the coming hours. This information and actions should be exchanged seamlessly through multiple interaction channels. How do we create a consistent interaction between home and householder, across times and purposes?

Preferences and objectives remains abstract and should be built automatically, by combining all data and interactions to minimize direct user input. How does the home learn from available inputs the negotiability and the collaborative requirements of each appliance? How do elements of prediction, reaction and reflection elements make use of these preferences towards the same, abstract objectives?

To support a wider audience, multiple levels of abstraction should be accessible to householders. For example, a washing machine load could be represented by a set of instant power data points. Eco-feedback systems often rely on this technical view of data. An event ‘Running the washing machine’ could encapsulate this technical data. Activities could also group a set of events. For instance, ‘Doing the laundry’ would group the washing machine and tumble-dryer loads. The elements of the system could take advantage of these abstractions to ensure the optimisations remain coherent (e.g. making sure the system does not suggest to run the tumble-dryer before the washing machine).

Handling the multiple versions of data is also a challenge. For instance, we consider the variable ‘washing machine power consumption’, in kilowatts. The system monitors this variable from a smart plug providing the ‘actual’ value sensed from the environment. In addition, the system can generate predictions of this variable for the coming hours or days. These predictions can be used to create alternative versions for different optimisation plans. Finally, the reflective elements could detect a mistake in the data and create a corrected version.

Finally, there are a number of security and privacy concerns. While there are growing concerns about smart meters and sharing energy data with energy providers, these concerns start inside the home. How does the home ensure the privacy of each householder while increasing the collaboration? Furthermore, increasing the interaction capability will raise the security threat with more access and control opportunities.

While this thesis focuses on interactive Demand-Shifting, we believe the implications and challenges of a Digital Conversation go beyond this scope and are among the main challenges to address in digital tools.

8.4 A DIGITAL CONVERSATION FOR INTERACTIVE DEMAND-SHIFTING

We informed the Digital Conversation from the user studies and we highlighted its impact and challenges. In this section we aim to provide a concrete example of a Digital Conversation for interactive Demand-Shifting. To this end, we use Kephart and Chess’s model of autonomic system (Kephart & Chess, 2003). The vision of a system composed of autonomic elements interacting together fits with the Digital Conversation described above. The MAPE-K loop models the process of an autonomic element, through **M**onitoring, **A**nalysis, **P**lanning and **E**xecution with its own **K**nowledge.

Figure 8-6 depicts our vision of an interactive Demand-Shifting system as a set of autonomic elements. We can notice two important deviations from Kephart and Chess’s scheme: First, we consider all elements share the knowledge, monitoring and execution sets of mechanisms as common resources. Second, we complement the scheme with ‘Converse’, a fourth set of mechanisms shared across all elements to support the Digital Conversation between householders and autonomic elements. We represent these user interactions by a red character. In this section we detail an example of predictive, reactive and reflective autonomic elements and their collaboration.

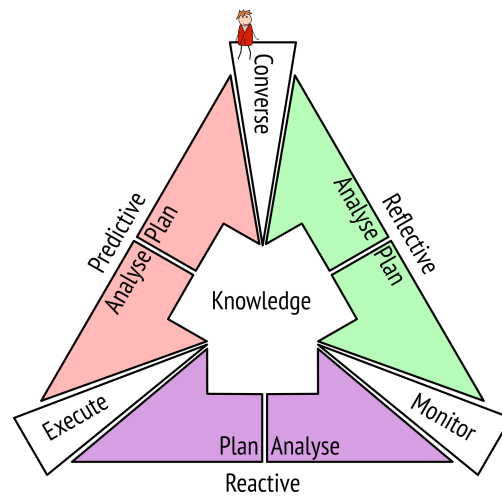


Figure 8-6 iDS as a system of autonomic elements.

8.4.1 PREDICTIVE

A predictive element looks ahead to anticipate over or under electricity generation and consumption. It requires building predictions, looking for optimisations, conversing with users and planning actions in advance. **Figure 8-7** illustrates the predictive element as a MAPE-K autonomic loop (Kephart & Chess, 2003).

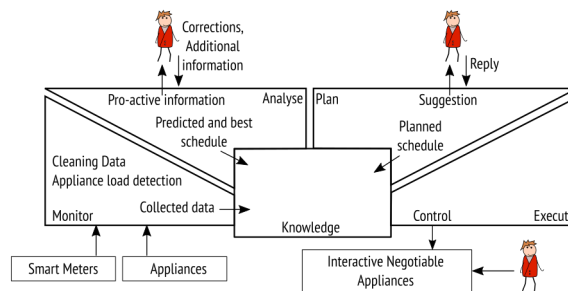


Figure 8-7 Predictive element.

Analyse

To anticipate, the system generates or collects predictions to get insights on both the production and consumption. This information forms a forecast schedule, that is a view of the expected behaviour of the system. We presented existing prediction algorithms from the literature in Chapter 2 (p.41) and we described our implementation of predictions in Chapter 6 (p.108) to support our interventions. Once the predictive element has a predicted view on what is going to happen, it can look for optimisation. Looking for an optimised schedule means searching among all potential solutions which, given a set of objectives, perform best. However, the validity of a solution has to be checked. Scheduling two washing machine cycles at the same time or running the tumble-dryer before the washing machine are physically impossible or absurd. Because we are dealing with a real world environment, all solutions are not valid, even for an ‘ideal’ schedule. We defined a set of ‘operational constraints’ that any solution has to comply with to be evaluated:

- ‘One load at time’ constraints ensure that an appliance is not running multiple jobs on the same period;
- ‘Load sequence’ constraints ensure that loads are played in a specific order, to comply with a routine.

To find an optimised schedule, the system needs to compare two schedules based on the 3 objectives. As these three objectives are totally independent, we used the partial order defined by the Pareto dominance to compare two schedules. Thus our system will obtain a set of optimised solutions that are not comparable between each other and constitute a Pareto front.

At this stage, the system can converse with the householders to share the predictions and potential optimisation as information. The householder should be given the opportunity to correct or provide additional information.

Plan

Based on the analysis element, a fully automated system would have all the necessary information to take decisions and schedule the appliances’ load. However, the system needs to collaborate with the householders. The planning element relies on an action plan and an implicit contract established with the householders.

An action plan is a schedule of appliance loads that would allow to improve the efficiency of the household’s consumption. From this stage, the system relies on the householders to agree or implement this action plan. We formalise this user interaction through ‘suggestions’ in the next section. However, the system cannot realistically count on the householder to respond and needs to take a temporary decision. Thus, we consider the predicted schedule as the planned schedule – i.e. the schedule we expect to happen – because it is the closest from what is going to happen in the absence of householders’ response. However, we keep the action plan as an implicit contract engaging the system on a suggested solution for a given time. No other suggestion will be made before the suggestion expire, avoiding householder confusion.

A suggestion relies on the action plan, composed of a list of appliance load and suggested start time. The system decides to send a suggestion to the user based on two criteria. First, the solution has to reach a required level of benefits for each objective. This level is arbitrarily defined but should be inferred from the user response over time. This level filters the solutions keeping only those with a ‘high’ potential of improvement. Second, the system checks it is not engaged by an implicit contract. The suggestion contains an

expiration date, defining a period during which the system cannot change its ‘mind’, even though a better solution could be found (implicit contract).

The user can accept a suggestion and ask the system to apply it automatically under a set of constraints. For example, the system suggests shifting the start time of the dishwasher by 2 hours. The user can get the dishwasher ready and let the system manage the time with a deadline at 6P.M. at which the load has to be done. Then, the system has the flexibility to update the best start time in case it has changed. Otherwise, the users can simply ‘Accept’ or ‘Reject’ the suggestion, notifying the system about their intentions to apply the suggestion. However, in both cases the users can change their mind without informing the system. It only increases the probability that the user will follow the suggestion or not. Finally, without a reply from the user the system has to keep the suggestion until it has expired before generating a new one.

8.4.2 REACTIVE

In contrast with the predictive element focusing on future events, the reaction is focusing on real-time events. It is continuously monitoring the current balance between consumption and generation and keeps an updated list of potential actions to apply, trying to maintain the balance close to zero. **Figure 8-8** illustrates the reactive element as a MAPE-K loop.

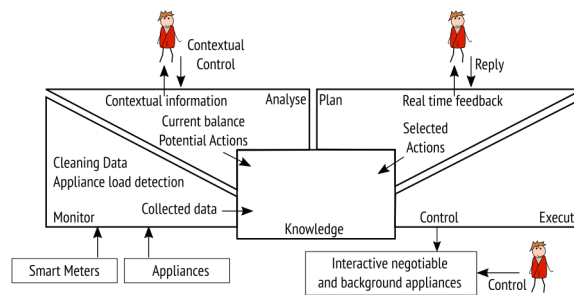


Figure 8-8 Reactive element.

In order to react, the system builds and keeps updated at runtime a list of potential actions that can be undertaken in case of under or over consumption. This list contains the types of appliances: interruptible, shiftable and reducible. Each action includes an expected impact on the system to indicate whether it will increase or decrease the overall consumption and for how long. The system updates the list when an appliance status changes. For example, when the refrigerator turns on, the system creates a potential action that could turn off the refrigerator for 15 minutes (a reasonable period without knowledge about the actual refrigerator temperature). The actual choice of the action to undertake is decided in the planning part.

The real-time analysis provides a support for householders at home who want to know if it is a good time to run an appliance. During the interviews we emphasised that some participants were keen to know what the current balance was, information they had to figure out by themselves looking at the real-time charts provided by the HEMS.

Plan

The reactive part is in charge of choosing which actions to undertake among the set of potential actions that have been determined by the analysis element. This decision is based on the current situation and the expected impact associated to each actions. Our system chooses an action that is supposed to limit either the export or the import of energy. For example, when the user turns on an appliance (that has not been anticipated by the system), the system quick corrective action can be to turn off the refrigerator for a small period of time in order to reduce the peak of electric demand. To decide the exact action to undertake, our system ranks the set of possible actions according to their expected impact on the system and choose the one that will bring the system as close as possible to a state where the exact amount of locally produced electricity is consumed.

At this stage, the users can be notified of such decisions to keep them aware of what is happening. The objective is not to overload users with notifications but to provide the information at places the users expect them. For example, in the study by Kobus and colleagues the washing machine embedded display was showing *'waiting for the sun'*. We could imagine an extension of such message like *'In pause, waiting for the coffee machine'*.

Collaboration

On one hand, the predictive element looks ahead to define a better energy plan. On the other hand, the reactive element executes potential actions at real time to maintain the best balance. While both can work on their own together or once at a time, there are opportunities for collaborations. The plan produced by the predictive element can be used in two ways to enhance the reactive process. First, the plan provides a list of appliances to be started automatically at a given time, that have been negotiated with the user. This provides potential actions: starting scheduled appliances a little bit earlier or later than planned. Second, the reactive process can base its decision on the planned balance instead of the actual balance.

By sharing executed actions and plan divergence, the reactive element can also enhance the predictive element. Instead of computing predictions and optimisations at regular time it becomes possible to run them whenever the actual balance is diverging from the planned balance.

8.4.3 REFLECTIVE

In such an autonomic system, it is important to perform a constant evaluation of the system. There is no possible improvement without evaluation. This includes the performance of the system towards the given objectives, but also the evaluation of the predictions, optimisations or the way the system deals with the user.

Figure 8-9 illustrates the reflective element as a MAPE-K loop.

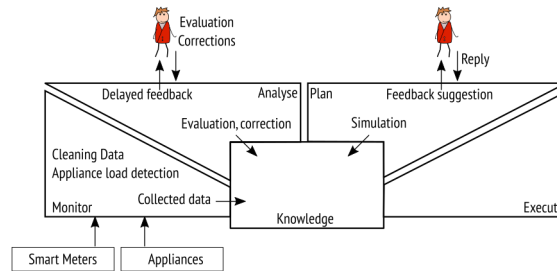


Figure 8-9 Reflective element.

Analyse

The role of the evaluation element is to mine the knowledge accumulated so far to detect and correct errors, and analyse the data over medium and long term to evaluate the performance. While this stage could involve multiple interventions and data mining on the data, we currently simply crawl the data to build statistics. Such information could serve for example, the delayed feedback intervention in the washing machine studies. In fact, the reflective element could provide detailed tendencies on the system performance. Especially, how much benefits have been realised for each objective? During the interviews, most participants were also keen to evaluate the payback of their solar PV over a long period.

Plan

The objective in this phase is to learn what could have been done better to improve the system for the future iterations. This is where the Best Shifting Algorithm we used during the washing machine studies takes place. The system evaluates the best way to organise the loads during the past days to provide a better picture of the system performance – how did the system perform compare to the best shifting achievable?

At this stage, the reflective element would be able to generate similar visualisation than during our PDA. For example, the actual and shifted washing machine loads over the past month. Participants were keen to have a way of looking at such report directly on the system.

Collaboration

Similarly to the predictive and reactive elements, the reflective runs on its own, providing the performance of the system. However, this reflection could be pushed further in collaboration with the other elements. The predictions, optimisations and plans provided by the predictive process can be evaluated against what actually happened and taken into account for the future iterations. The expected impact of the potential actions executed the reactive process can be compared against the actual impact on the system and used to refine expectation of future potential actions.

8.5 CHAPTER SUMMARY

In this chapter we combined the findings of our four user studies with existing literature to formalise a conceptual framework for a Digital Conversation relying on four key elements: time and purpose of interaction, contextual and long term objectives, audience and participation and technology enablers. Then, we described the Digital Conversation, connecting these key elements, and we presented the implications and challenges. Finally, we proposed a concrete example of Digital Conversation for interactive Demand-Shifting .

Providing an initial step towards engineering solutions that would follow the conceptual framework, we emphasised the challenge of building a flexible and consistent system to support a digital conversation. We highlighted the need for an explicit formulation of user interaction mechanisms in self-adaptive system, suggesting an extension of the MAPE-K loop with ‘Converse’. Finally, we stressed the need for close collaboration between the multiple elements in the system.

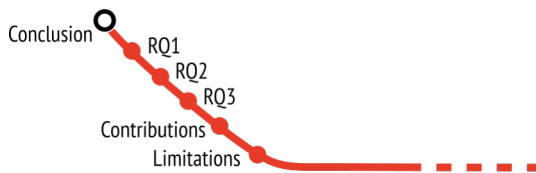


Figure 9-1 End of the Demand-Shifting line, red thread of this dissertation.

Conclusion

Towards Sustainable Opportunities

‘We can only see a short distance ahead, but we can see plenty there that needs to be done.’

ALAN M TURING, COMPUTING MACHINERY AND INTELLIGENCE, 1950

Domestic micro-generation will play a major role in the future energy strategy. Yet this local generation relying on solar or wind energy cannot be controlled and is out-of-sync with householders’ consumption, creating a domestic energy gap. Meanwhile, early evidence has begun to show an impact of those emerging energy technologies on householders who engage into new energy behaviours, trying to make the best out of their local generation. This thesis has set out to understand the potential and the barriers of interactive Demand-Shifting in the context of domestic solar electricity generation and provide the digital tools to support practices emerging in this context. This project stands as a new research approach by supporting emerging practices rather than pushing for behaviour change and consumption reduction. In this conclusion chapter, we go back to the research questions we formulated in the introduction and we address them, assembling the pieces collected throughout the thesis. Then, we discuss the main contributions of this thesis as well as the limits of this research.

9.1 BACK TO THE RESEARCH QUESTIONS

At the earliest stage in this thesis, we stated the following research question:

How can digital tools leverage Demand-Shifting practices in the context of domestic micro-generation?

We broke down this question in three sub-questions:

RQ1. How do Demand-Shifting practices take place in the context of domestic solar generation?

We addressed this question through a methodology combining quantitative and qualitative data to evaluate not only the technical potential but also householders' engagement and willingness.

To make Demand-Shifting possible requires an initial energy awareness which is brought by the solar PV. We observed that most participants who engage in the process of solar PV, also engage in making the best use of it (§4.4.1). Differences were visible within households between members who were more involved in the decision-making around solar PV (§4.4.3).

For all participants, the main difficulty was the time. It is time-consuming to collect and process the relevant information and take decisions about Demand-Shifting (§5.4.3), knowing this process cannot be done one for all. For some, this decision process became a routine in itself (§5.4.5). Thus, manual Demand-Shifting requires the combination of multiple pieces of information often from different tools (§4.3.2), leading sometimes to hazardous decisions (§4.4.2). Despite the willingness of most participants, they do not want to spend much time of Demand-Shifting and they are not always at home when it would be the right time to intervene.

Both laundry and mobility routines involve several householders or at least a householder who is not the 'energy manager'. As highlighted in the literature, energy tools, as they are called, focus on the energy management for the energy manager. Our findings have shown that supporting domestic routines instead of focusing on energy was allowing a widening of the audience (§6.6.3). The system is no longer interacting only with the householder interested about energy but also with any householder taking part of the domestic routines.

From participant's energy data we observed that there was a significant room for improvement through Demand-Shifting (§0). Discussing our observation in collaboration with the participants, we understood that data were not reflecting the effort that participants were already putting into manual shifting (§5.3). It highlights the motivation of engaging in such a process, but also the requirement for digital tools to support this process.

In the case of the EV, even more challenges are taking place as it is a new appliance. We highlighted that self-sufficiency and green driving were directions that participants were looking for but the high consumption compared to their local generation discouraged some of them (§7.1.2). While we show that EV electricity consumption at home were of the same magnitude as the local generation (§7.2.3), a choice remained whether they wanted to power the EV or the other appliances with their local generation. Generally, we highlighted that domestic EV routines require more support. In this context, Demand-shifting should be blended in a larger set of support for EVs as a new form of home electricity consumption (§7.5.3).

RQ2. What are the requirements for the interaction between system and householders when the aim is to support Demand-Shifting practices?

So far most of the home energy research focused on eco-feedback and energy consumption reduction, relying on householders' energy awareness and pushing them towards energy consumption reduction. This research project relied on energy awareness too: that of making electricity generation more visible and bring it closer to the end-user. However, we observed wide variations in the level of awareness between our participants, suggesting that more explicit information is required helping them to understand this technology and how they can benefit from it (§4.4.2). This eco feedback should set the electricity consumption in the context of the electricity production, both from the domestic micro-generation and from the electricity grid. On top of this initial awareness, we highlighted the need for more interactive exchanges between the home and the householders, characterised by:

- The time – **Reflecting on the past is not enough.** As the best strategy evolves from day to day based on the weather and needs, proactive information is key to support Demand-Shifting practices (§6.4.2). This also goes for the way this information needs to be delivered and actions automated, which can be either before, during or after an energy event (§6.5.2).
- The objectives – **Focusing on energy consumption reduction is not enough.** There are multiple and changing objectives over long and short term. It is important to support householders' objectives to keep them engaged, whether they are aiming to get the laundry done before noon, or whether they take pride in consuming as much of their own local electricity as possible. We believe that supporting householder's practices is more sustainable than driving behaviour change.
- The audience – **Talking to the 'Resource Man' is not enough.** Adapting the level of information is really important depending on who is the receiver of the information. We highlighted that supporting electricity Demand-Shifting means negotiating with the right persons (§6.6.3), either it is the head chef, the driver, the laundry conductor or any other routine manager. Widening the

energy audience is a way to support Demand-Shifting by talking to the person in charge or affected by the intervention.

- The appliances and activities – **Looking at the energy profile is not enough.** Closely related to a wider audience and objectives, the energy should remain a resource. Householders should be offered management support for activities and appliances with higher levels of modelling of routines instead.

In the case of emerging appliances such as the EV, additional support is needed even before thinking about shifting the charging time (§7.4). Support for Demand-Shifting should take place seamlessly among appliance-specific support requirement (§7.5.3).

RQ3. How can we design a realistic and interactive digital system to support domestic Demand-Shifting?

By addressing RQ1 and RQ2, we highlighted the requirements for digital tools to support domestic Demand-Shifting. We described an interactive Demand-Shifting (iDS) framework, formalising these requirements with the key elements: times, objectives, audience and appliances.

We identified seven key times of interactions, complementing the typical eco-feedback with predictive information and proactive suggestions. An interactive Demand-Shifting system should facilitate predictive, reactive and reflective features and ensure the consistency among them. We emphasised the need for multiple objectives following long-term motivations and short-term situations. Finally, we relied on our experience from the user studies and existing taxonomies from the literature to build a flexible taxonomy of appliances.

We introduced the ‘Digital Conversation’ to design a system that meets the iDS framework requirement. We specifically focused on consistency in such an interactive and time-aware system and we provided a solution for this challenge. Considering requirements and solutions we described how to design a realistic and interactive Demand-Shifting system.

9.2 CONTRIBUTIONS

While the key for sustainable energy use might appear as simple as reducing the energy consumption, we provided a detailed **understanding of the energy gap** problem and the complexity of the micro and macro electricity grid infrastructure. In the quest for sustainable energy, the small yet effective interventions are often overlooked because of a lack of understanding of challenges and opportunities. This project highlighted limited financial benefits for individual householders. However, it has the power of being easily

scalable to all households, representing a significant impact on the electricity grid. By 2020, the current national rollout will bring a smart meter in every household in the UK. Meanwhile, the combination of Internet of Things technologies taking place in every home appliance with the capability of disaggregating each individual appliance load through a single electricity meter will bring all the ability for Demand-Shifting at no cost.

The overarching goal of this research is about **supporting sustainable energy** consumption. Practices are likely to be more sustainable over time if they are initially naturally implemented by the householders themselves instead of being pushed towards them in an effort to change their behaviour. This work stands as an emerging direction for research into supporting emerging energy behaviour rather than driving behaviour change. Specifically, we uncover what motivates and drives householders, one of the key findings is to enlarge the participation among members of the household.

Already emphasised in the literature, domestic energy management needs to be looked at through the lens of activities and routines rather than direct energy consumption. We built on this stand with the digital conversation, allowing **higher level interactions** between the householders and the system. It builds the foundation for a negotiation towards a sustainable energy management.

Throughout the thesis we stressed the importance of timings of interventions. Demand-Shifting is not only about finding the right time to consume electricity but also the right time to interact with the householders. Specifically, we emphasised the need for **proactive suggestions and contextual interventions**, offering householders the opportunity to intervene on time with the necessary information and support.

With deep user and energy dimensions, we formulated a **taxonomy of appliances**. This taxonomy considers the real world insights collected throughout this thesis, reflecting the necessary diversity and flexibility of appliance management. In combination with the digital conversation, they provide the foundation for more sustainable domestic energy management system for the whole household.

To build a more accurate understanding of the domestic routines we used a mixed method approach. Building on recent innovative methods, we designed and implemented the **Participatory Data Analysis** (PDA) which combined quantitative data and qualitative data to analyse the domestic context in collaboration with the householder (§5.1, §7.4). This method has been an effective way for both washing machine and electric

vehicle studies to confirm initial interpretations, but also to enrich both quantitative and qualitative analysis with precise elements of context. We believe this method strengthens the results of this research and complements the tool box for in-the-wild research, especially in highly contextual environment.

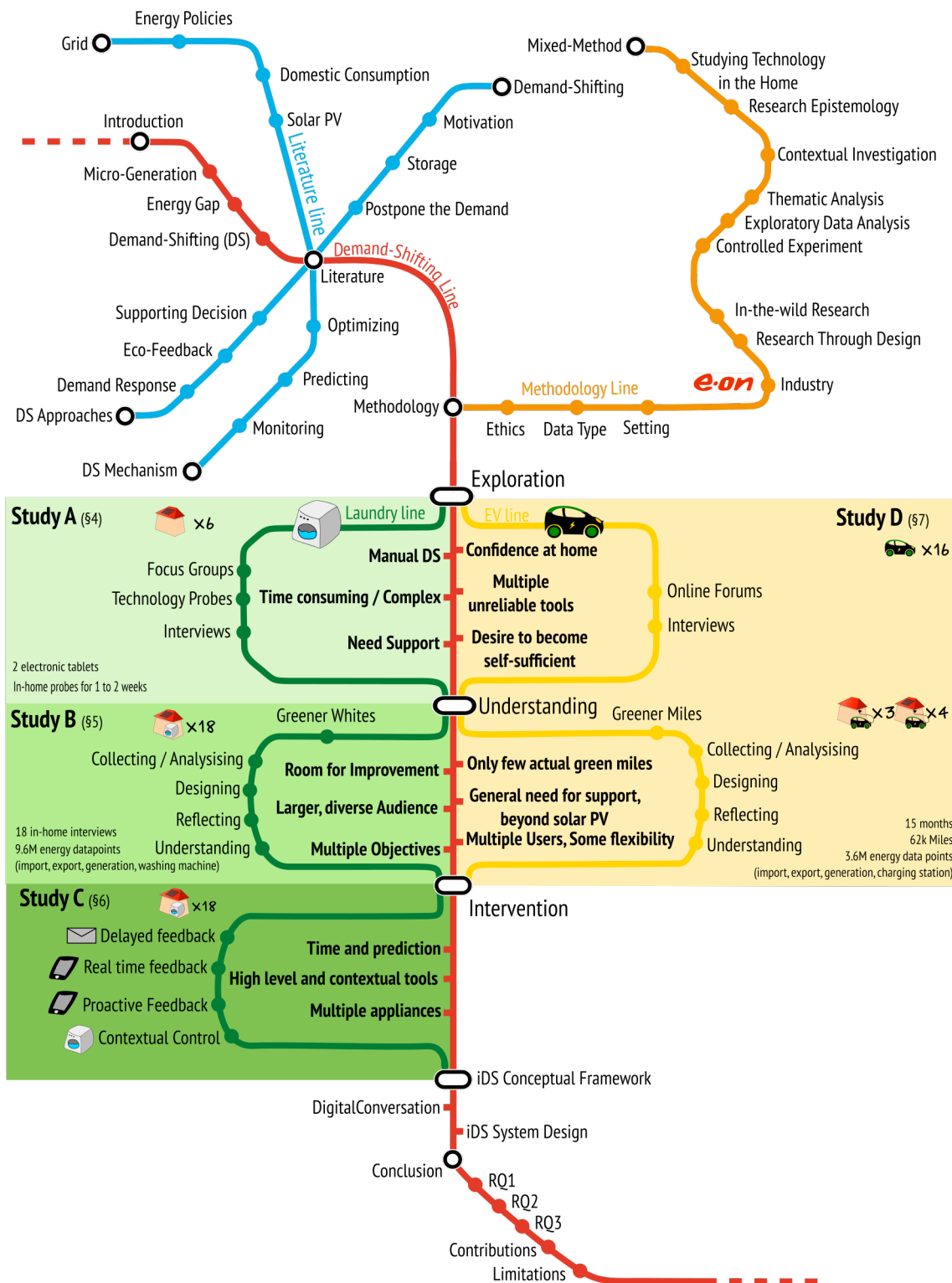


Figure 9-2 Thesis map.

9.3 LIMITATIONS

This research project stands as an exploratory study which does not provide statistically significant results but rather a deep insight of two domestic routines in the context of micro-generation and how it impacts the design of home digital tools. We relied on a limited number of participating households and technical constraints led us to take on board the same houses for several studies. In combination with their participation in the E.ON trial for a couple of years, we suspect this made them more ‘energy aware’ than typical householders. The sequence and the combination of multiple interventions over time might also have affected the way householders react to them.

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